MILITARY GEOGRAPHY: THE INTERACTION OF DESERT GEOMORPHOLOGY AND MILITARY OPERATIONS

by

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ABSTRACT

This research investigates the interaction of desert geomorphology and military operations. Battles throughout history were fought in desert regions and the future is certain to hold additional conflicts, particularly in the Middle East where Operation Iraqi Freedom currently rages at the time of this writing. Regardless of the frequency of desert warfare, this environment is not always well understood. Reliance on visual appearance and generalized maps of desert regions may cause perceptions that do not reflect reality. The first part of this research reassesses prior assumptions of geomorphic homogeneity in the easily accessible western Mojave Desert, California by comparing a United States Geologic Survey (USGS) geologic map with remotely sensed Thematic Mapper Simulator (TMS) imagery, using a Geographic Information System (GIS). Imagery is classified, then compared and correlated with the geologic map to produce a more accurate assessment of the surface that reveals significant complexity. Strategically important desert regions worldwide are not as well studied or accessible as the Mojave Desert, which suggests that these areas may also be misperceived.

This research then explores a bi-directional linkage between geomorphology and military operations, first by investigating the influence of geomorphic processes on the conduct of military operations, then by considering the effect of military operations on the physical environment. A conceptual model that emphasizes fundamental geomorphic processes and conditions is developed to examine warfare in non-temperate environments. The model is successfully evaluated in desert regions and validated through the use of historical examples. It provides an alternative and complementary technique to examine the environment's operational effects on troops, equipment, and

tactics, compared to more traditional, applied work that focuses on how to cope with these conditions.

Last, this research examines the impact of 60-year-old tank maneuvers on desert pavement in western Arizona using a nuclear density gauge, Backscatter Electron (BSE) microscopy, and various field methods. Alterations made to the pavement by tank passage support natural moisture penetration into the subsurface at the study site, which enhances and is a necessary condition for vegetative growth and some pavement formative processes.

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CHAPTER I: INTRODUCTION

Geomorphology is, in its simplest form, the study of landforms (Ritter 1978). Geomorphologists not only strive to understand terrain, but also the dynamic processes that create and destroy it. Likewise, understanding the complexity and character of terrain is essential to army officers and soldiers, as it constitutes the physical environment in which they must make life or death decisions. The belief that the environment is neutral in war, simply a stage upon which battles are fought, is nonsense. The side that understands the interrelationships and dynamics of terrain, weather, soils, vegetation and climate better, has a distinct advantage. History is replete with examples.

The purpose of this research is to explore the interaction of geomorphology and military operations. Soldiers perceive terrain largely in the context of applied problems. A tank commander ordered to take the hill does not necessarily care why the hill exists. He is concerned about the geomorphological aspects of terrain that may provide an advantage - is there a wadi that allows a covered and concealed approach? Can the tank's armor penetrator punch through defensive earthen berms and destroy enemy positions? Conversely, Geomorphologists see the hill in both theoretical and applied terms. What is the underlying geology? What processes formed the hill and what processes are at work denuding it? How can geomorphology solve the soldier's challenges?

This dissertation investigates both the geomorphologist's and the soldier's perspective of the physical landscape. I first consider the perception of homogeneity in desert terrain by quantitatively evaluating surface complexity of an easily accessible, yet seemingly homogeneous desert region. If perceptions of such a region are not accurate, it

is possible that poorly accessible, but geopolitically more important desert regions worldwide are also misperceived, and this has implications for both civilian and military applications. I then explore the bi-directional linkages between geomorphology and military operations. Chapter III introduces a conceptual model to analyze the effects of geomorphic processes and conditions on military operations. Chapter IV presents a geomorphic interpretation of the impact of military operations on desert terrain. This research combines military geography with the tradition of geomorphic analysis.

This introductory chapter explores the nature of military geomorphology and its relationship to the parent discipline of geography to provide context for this research. It reviews key military geographic ideas in the United States in the 20th century to the present and concludes with a discussion of the relevance of this dissertation to modern military geomorphologic thought in the United States. It introduces specific areas of study that are presented herein.

Background

The Nature of Military Geomorphology

The discipline of geography is often expansively presented in academia as having two major divisions: physical and human (Clark 1988). At the broadest level, some leading university geography departments, including Arizona State, divide their study of geographic concepts primarily into these two fields, assigning different course offerings based on these designations. Other departments, such as the United States Military

Academy at West Point, present a third branch incorporating geographic tools and techniques such as GIS and remote sensing, amongst others. In response to recognition that most of the world's problems inextricably involve both the human and physical environment simultaneously, and that one of geography's distinctive and coherent perspectives is that of synthesis, geographers sometimes also embrace a fourth, complementary element of the discipline that focuses on the overlap of both physical and human geography. Environmental geography combines the study of both physical and cultural elements of the discipline, specifically examining the interactions between people and their environments (Cooke 1992; Department of Geography & Environmental Engineering 2003). Figure 1-1 is a Venn diagram illustrating the relationship between these disciplinary categories.

Military geography, as a sub-discipline of geography, is generally recognized in the broadest sense as the application of geographic principles to military affairs or military problems (Peltier and Pearcy 1966). This definition implies that the sub-discipline draws from all (physical, human and techniques) aspects of the discipline. Another definition of military geography is the study of the relationships between people and the physical and cultural environment insofar as it pertains to the employment of military power (Department of Geography & Environmental Engineering 2001b), which again emphasizes the overlap of these divisions. Perhaps the most relevant and functional definition in the context of this research is the application of geographic information, tools and technologies from both the physical and human sides of the

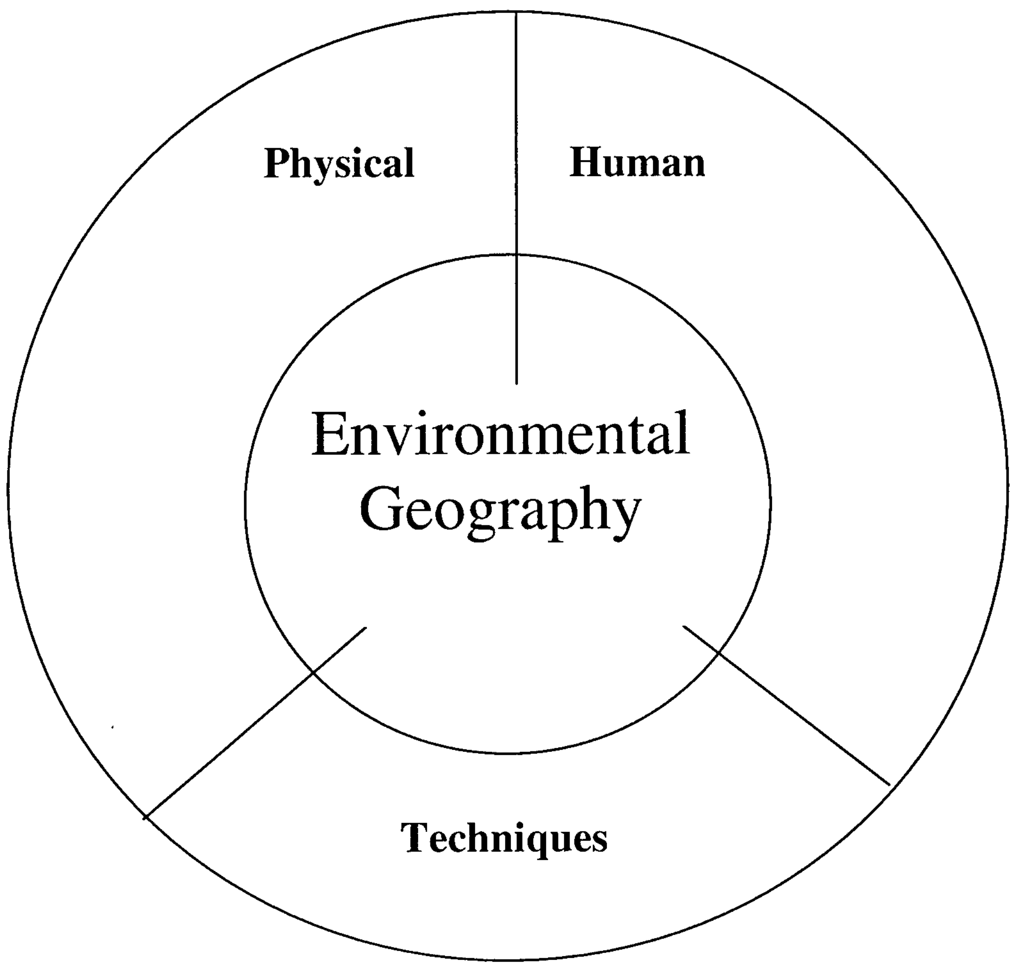


Figure 1-1. Venn Diagram showing relationships among what some consider to be traditional divisions of the discipline of geography and the sub-discipline of environmental geography.

discipline to solve military problems (Department of Geography & Environmental Engineering 2001b). Military geographers therefore, are concerned with all aspects of the study of geography, but are particularly focused on the confluence of the physical and human realms, much like environmental geography. Military geomorphology, as a sub-discipline of military geography, seeks to provide solutions to military challenges that are set in the physical environment, yet by its very nature as a function of military inputs and challenges, it inherently includes aspects of the human and techniques portions of the discipline (Figure 1-2).

Military Geography in the United States

Military geography is a discipline as old as war. Its roots can be traced to the first recorded battle in history, which occurred at Megiddo (circa 1479 BC), located northwest of the present Israeli port city of Haifa (Thompson 1984; Duncan and Opatowski 1998). Subsequent history is filled with writings that discuss military geography in one form or another from the Peloponnesian War through the Roman era to the modern era. The key to the discipline's popularity has always been its utility to the successful prosecution of war.

In the United States, the first formal demand for military geography occurred in response to WWI. Emphasis focused on analysis of the physical aspects of terrain with particular respect to application of geographic principles and knowledge to solve the military's wartime challenges (Palka 2001a). Douglas W. Johnson published two key works during this time frame, *Topography and Strategy in the War* (Johnson 1918) and

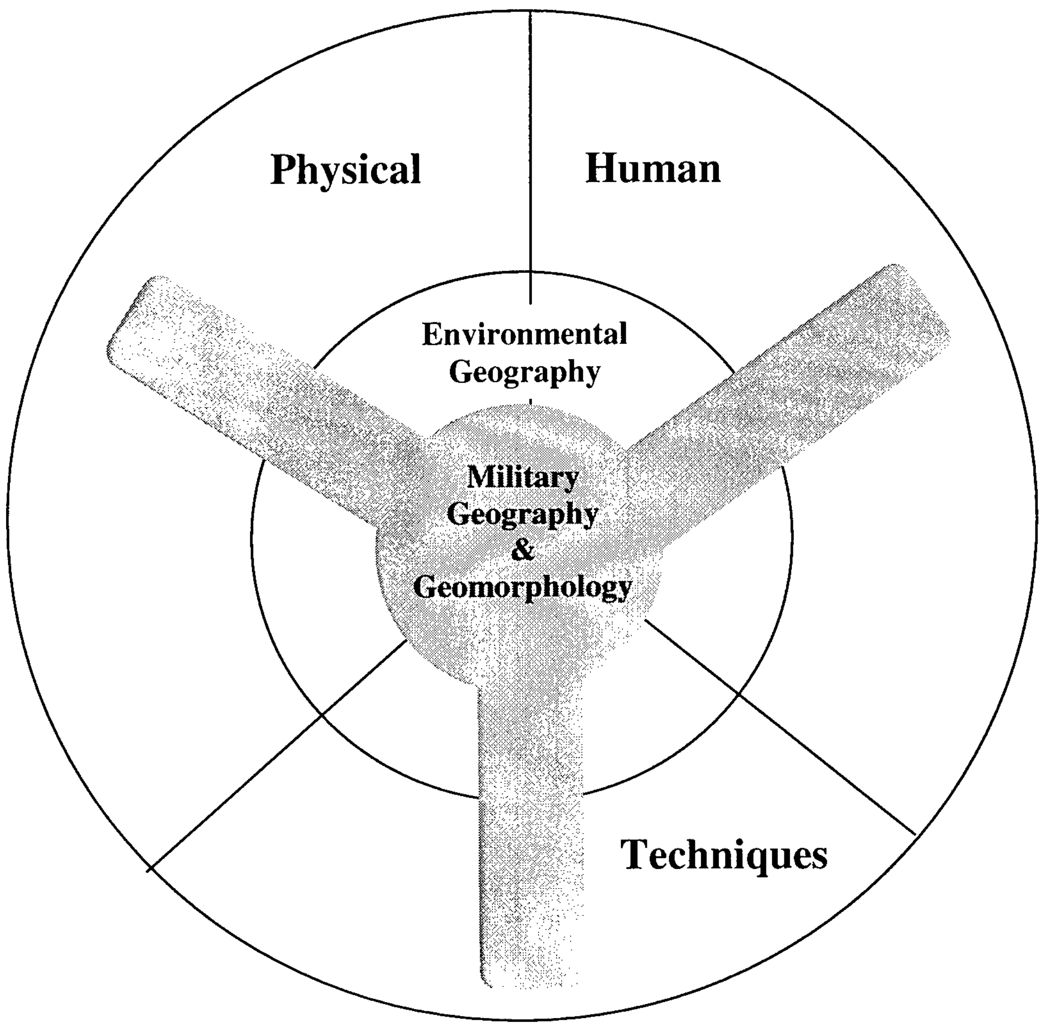


Figure 1-2. Venn diagram showing the relationship of military geography to the larger discipline. Military geomorphology, as a disciplinary subset of military geography, encompasses the same relationships with emphasis on the physical dimension.

the most widely recognized military geographic work of the era, *Battlefields of the World War, Western and Southern Fronts: A Study in Military Geography* (Johnson 1921). By the end of the war, the utility of geography to solve wartime problems was well understood in America.

The importance of military geography grew during World War II. This global war highlighted the need for regional geographic knowledge in the United States. "Examples of the lack of appreciation of the geographical factor by the military are numerous during this period" (Jackman 1962). The need was met over the course of the war. Military geography progressed beyond the basics of collecting and compiling data, to production of useable intelligence on regional physical and human aspects of the landscape. Efforts culminated in the Joint Army and Navy Intelligence Studies (JANIS) "which were essentially the regional geographies of selected theaters" (Palka 2001a). Military geography expanded greatly during this effort, but its focus remained on warfighting.

The war in Vietnam took a devastating toll on the popularity and contributions to military geography, and its reputation in academia suffered accordingly. A substantial portion of American society was not behind the war effort, and university and college professors in particular disdained an association between the military and geography to be unworthy or unclean. During and after the war, military geography reached a nadir in popularity, particularly since it had retained its association with a wartime focus.

This condition continued until after the Cold War. Despite the immutable importance of geography in the Gulf War of 1991, this conflict did not contribute

significantly to the resurgence of the field, but the end of the Cold War proved to be a major catalyst (Palka 2001a). Changes in the strategic situation caused dramatic changes in U.S. Armed Forces structure, size, and postings and ushered in an era where military forces were commonly required to perform missions that did not involve traditional warfighting. It created a substantial increase in the nation's involvement in peacetime operations and Military Operations Other Than War (MOOTW) throughout the world. In the 8 years between 1989 and 1997, for example, the US Armed Forces participated in an astounding 45 MOOTW, more than three times the number conducted during the entire cold war era (Binnendijk 1998; Palka 2001a). The importance of these type operations in the new geopolitical environment required their inclusion within the definition of military geography.

In 2000, Palka and Galgano (Palka and Galgano 2000) advised a formal expansion of the scope of military geography to encourage work in peace and MOOTW realms. Today, military geography is undergoing a resurgence. Changes in world affairs attendant to the end of the Cold War, the conduct of the Persian Gulf War in 1991, the recent terrorist attacks on the United States, coalition forces activities in Afghanistan and Iraq, have piqued American interest in military geography at the turn of the 21st century. Recent landmark publications regarding the subject exemplify this resurgence (Collins 1998; Underwood and Guth 1998; Winters, Galloway et al. 1998; Palka and Galgano 2000; Ehlen and Harmon 2001; Palka 2001a; Doyle and Bennett 2002). Other indicators of recent popularity include the 1996 re-establishment of the Military Geography Specialty Group in the Association of American Geographers, which now enjoys a large

number of attendees at the annual meetings and 2 to 3 paper sessions each year. Notably, the president and vice president of the group are civilian professors. In the summer of 2003, a Military Geography and Geology Conference will be held in response to growing demand to provide another venue for exchange of ideas and encouragement for future work (Association of American Geographers 2003). It is appropriate and timely at this juncture in time to conduct research examining linkages between geomorphology and military operations as the character of warfare changes over the foreseeable future, making contributions of such research particularly valuable.

Military Geomorphology

Geomorphology remains the logical discipline to investigate military ground operations. The study of landforms encompasses formation, denudation, and the complex interrelationships and dynamic processes at work in all aspects of landform evolution. Understanding terrain that is explained by geomorphic processes is fundamentally and inextricably linked to the successful execution of ground warfare (see Garver and Galloway 1984; United States Army Armor School 1993; Sun-Tzu, Sawyer et al. 1994; Collins 1998; Winters et al. 1998).

Historically, misperception of climate, soils, vegetation, weather and terrain has been a factor in military reversals. Preconceived ideas of environmental conditions or the failure to anticipate dynamic processes through ignorance will never fully be remedied because of the complexity and lack of clarity that are inescapable conditions in conflict. Regardless, this paradox justifies the need for military geomorphologists to pursue

avenues of explanation in regard to linkages between military operations and geomorphology. Chapter II in this dissertation demonstrates the complexity inherent in desert areas that may appear homogeneous to laymen and to scientists. Chapter III examines the influence of dynamic geomorphic conditions on the conduct of military operations, and Chapter IV explores the effects of military operations on a particular type of terrain, desert pavement.

Specific Areas of Study

Chapter II: Reinterpretation of a Landscape in the Western Mojave Desert, California

Deserts are diverse regions, displaying a wide variety of landform combinations and environmental conditions. Large areas of deserts however, appear to be visually homogeneous especially in regions with relatively little relief such as the Sahara Desert in North Africa, the Syrian Desert and Rub Al Khali in the Middle East, the Simpson Desert of Australia, or the Sonora and Mojave Deserts of the southwestern United States, and in many other locations throughout the world. Despite apparent homogeneity, these desert surfaces may be particularly complex in composition and evolution, and understanding that diversity can affect decisions by military environmental managers and combat commanders. The first part of this dissertation reassesses prior assumptions of geomorphic homogeneity in the easily accessible western Mojave Desert by comparing a USGS geologic map with remotely sensed Thematic Mapper Simulator (TMS) imagery using a Geographic Information System (GIS). While no analysis is precise without field

truthing, there are desert areas throughout the world including portions of Afghanistan, Iran, Iraq, Libya, China and other locations where current conditions require remote analyses, yet ground truthing is not likely to occur. The information provided in this investigation offers a more thorough analysis of the terrain than is currently readily available through contemporary mapping sources, and it helps dispel misperceptions of desert homogeneity encouraged by visual appearance and generalized maps.

Chapter III: Physical Geography and Military Operations in the Desert Environment: A Model Examining Non-Temperate Warfare Environments

The commander who understands terrain gains advantage over the enemy. History is replete with military reverses and disasters that are a result of misconception or poor understanding of regional geomorphology and its effects. The second part of this dissertation creates and assesses a heuristic conceptual model that synthesizes physical geographical information on non-temperate operating environments with the effects these dynamic conditions have on the conduct of modern ground combat. The model systematically links key geomorphological factors gleaned primarily from applied studies with the conduct of military operations by explaining the dynamic processes related to each factor. The effects of these processes are then investigated using the variables of troops, equipment, tactics, and the use of historical examples. The robustness of the model is assessed in the context of harsh desert environments. If physical geography is indeed a key variable in military operations, it is critical to provide and then assess a coherent, understandable model useful for applied military science.

Chapter IV: The Effect of Military Operations on Desert Pavement: Case Study from Butler Pass, Arizona

The final part of this dissertation investigates the impacts that military operations have on desert terrain. Clearly, military operations affect the physical landscape in a multitude of ways and they create unique opportunities for research. Wheeled and tracked vehicle maneuvers, obstacle and fortification building and live fire exercises all have differing effects on terrain. This research explores one small part of this larger issue. It investigates tank track scars that were made on desert pavement in western Arizona in the early 1940s and are still evident today. Changes to the pavement because of tank maneuvers offers insight into the processes at work in desert pavement development and regeneration. Field methods including the use of a nuclear density gauge are used to examine the soil surface and the subsurface profile under disturbed and undisturbed pavement. These analyses are complemented by laboratory analyses including Backscatter Electron Microscopy (BSE) to examine subsurface conditions. A field experiment is used to determine relative moisture infiltration rates in and out of track scars.

Conclusion

Rapid changes in geopolitical conditions at the turn of the 21st century have fueled interest in the study of military geography and geomorphology in the United States. There exists no better discipline than that of military geomorphology to examine the linkages between the physical environment and military ground operations. The studies

contained in this dissertation, focused on desert regions, examine the complexity of terrain and explore key bi-directional linkages between the science of geomorphology and military operations. These linkages involve both the effects the physical environment has on military operations, and the effects military operations have on the physical landscape.

CHAPTER II: REINTERPRETATION OF A LANDSCAPE IN THE WESTERN MOJAVE DESERT, CALIFORNIA

Introduction

Misperception of operational environments has plagued military operations since the dawn of warfare. The outcome of battles and campaigns are often influenced by unexpected or misunderstood dynamic processes or conditions inherent to a region (see Winters et al. 1998). Comprehension of the operational environment, its variability and its complexity, is indispensable to success in warfare. Great captains of military history all demonstrated an uncanny ability to 'see the battlefield', allowing them to concentrate combat power at the critical place and time. Indeed, after studying the characteristics of successful combat leaders in the United States Army, *The Officer Personnel Management System Study Group* concluded that "… the ability to quickly, almost intuitively, tactically judge terrain was the most essential characteristic" of successful combat leaders (Department of Geography & Environmental Engineering 2001b).

'Seeing the battlefield' in the context of modern warfare requires more than innate ability, it requires a level of understanding of the physical environment and its effects. Success in modern warfare often depends upon the commander's ability to observe the environment and accurately process what is seen. The discipline most suited towards the study of the physical landscape is geomorphology. Scientists traditionally put observation at a central position in geomorphic research (Rhoads and Thorne 1996). While the tools used to observe landscape have changed tremendously with the passage of time, the requirement for observation as the key to understanding landscape remains

without challenge. At times, a desire to bring order to the complexity we see in landscape can result in simplification that may lead to false perceptions of the landscape, its evolution, and the effects it may have on military operations.

The western Mojave Desert has traditionally been viewed as largely homogeneous geomorphologically. It experiences low precipitation and high pan evaporation rates, and exhibits limited vegetation and enormous erosion potential. Large areas are buried in alluvial fill. "Alluvium appears to be banked deep against mountainsides or over the ascending surfaces of domes…" (Jaeger 1965, 24). Most research views the western Mojave as a relatively homogeneous sand sheet, with isolated bedrock outcrops, pediment-fan landscapes, and dry lake beds (Dibblee 1960; Dibblee 1967; Boettinger and Southard 1995). "The (western) desert … is virtually an alluviated plain containing irregularly trending bedrock hills and low mountains" (Dibblee 1967, 1). Geologic maps of the region show the vast majority of the area is covered by "alluvium," or "fanglomerate," terms that are at best ambiguous in the ability to discriminate composition or depositional attributes of the landscape (Figure 2-1). Even specialized treatments of regional geomorphology (e.g. Thornbury 1965; Hunt 1974; Graf 1987) focus on the eastern Mojave, leaving the visually monotonous and undifferentiated surface (Figures 2-2 and 2-3) a virtual blank in geomorphic synthesis.

Recently, in recognition of an information gap regarding the Mojave, the United States Geological Survey (USGS) launched a mapping project focusing on "…surficial

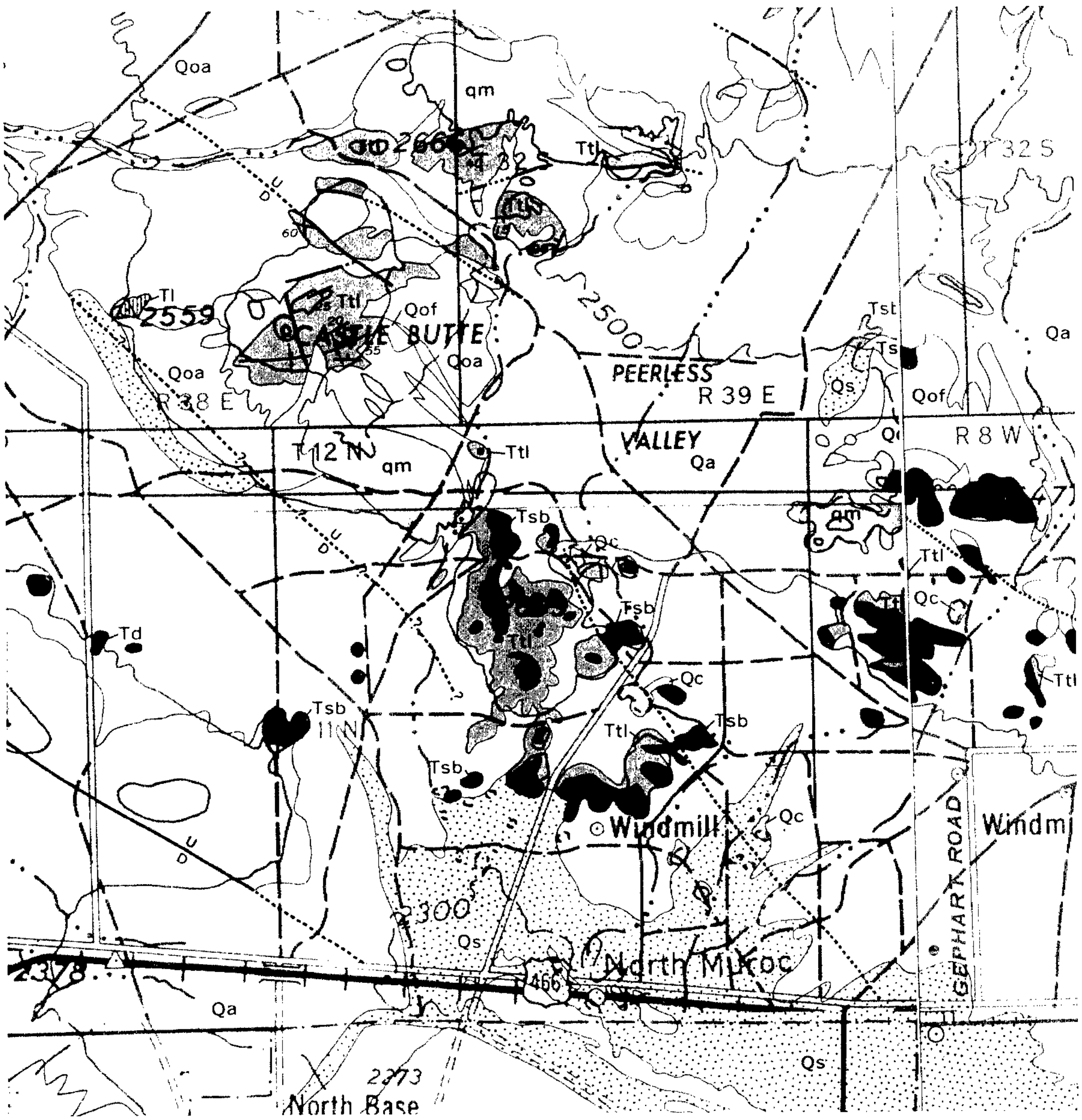


Figure 2-1. Section of USGS Geologic map showing a portion of the western Mojave Desert, including the study area. The yellow shaded areas represent alluvium, windblown sand, granitic fanglomerate, or fanglomerate (Dibblee, 1967).

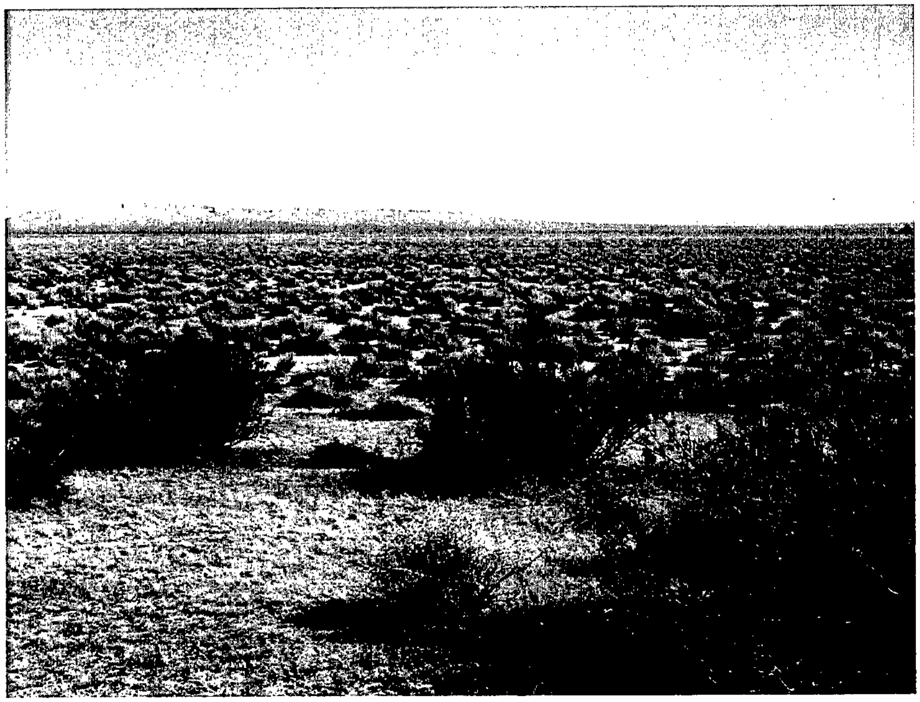


Figure 2-2. Study area looking south toward Leuhman Ridge where NASA Jet Propulsion Laboratory tests rocket engines.

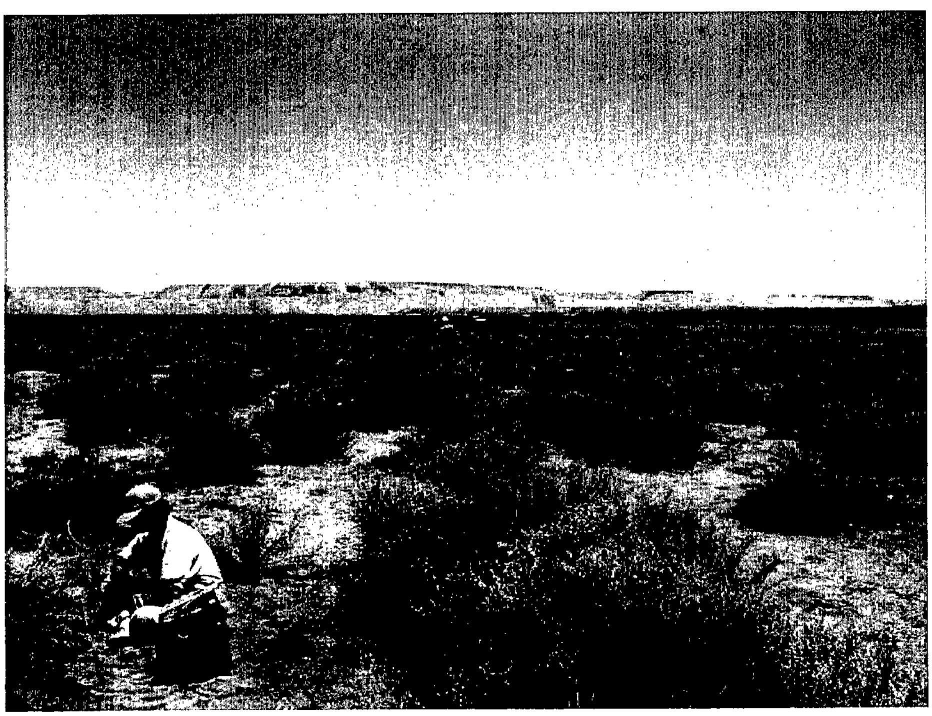


Figure 2-3. Study area looking east toward tailings from the U.S. Borax mine.

material because they are generally unmapped…" (Miller, Morton et al. 2003). This multiyear project is expected to lead to a more complete understanding of the region and result in improved land management applications.

Perceived homogeneity in the western Mojave relates to a wide range of issues. Understanding this region more completely has direct implications for management of urban encroachment, management of the area's natural resources, and understanding thepotential for future tectonic activity that is prevalent in the area. Located only 70 miles from Los Angeles, the western Mojave has long served as a recreation area for people in the southern California megalopolis who flock to the 'desert' (Birdsall and Florin 1985). Off-road vehicle use, livestock overgrazing, military combat training, agriculture and urbanization all affect this fragile desert ecosystem (Reynolds 1994; Duda, Krzysik et al. 1999). Increasing urbanization threatens to destroy potentially important archaeological sites, many of which are not fully understood and others that remain undiscovered (Stickel, Ritter et al. 1980). The potential for faulting in the region remains great given the proximity to the San Andreas, Garlock, Helendale, and Calico systems. More detailed mapping could reveal evidence of tectonic activity that threatens the area and is not well understood (see Levy 2000; Peltzer, Crampe et al. 2001).

The question of landscape complexity in the western Mojave relates to issues beyond regional impacts. When desert environments are not well understood, they can be misperceived. The western Mojave provides an excellent example. The region is easily available to researchers: it is located in the southwestern United States; it is comprised largely of publicly accessible lands; and numerous highways and roads lead to

and cross through it. Yet, despite its accessibility, this location, like many other desert regions worldwide including areas that are much more geopolitically important and less accessible (such as portions of Afghanistan and Iraq and others) is often described as homogeneous in maps and words. Homogeneous mapping and descriptives do not support perceptions of complexity that are closer to reality. These perceptions can lead to poor decisions in both civilian and military applications.

It is counterproductive to provide examples of misperception of the western Mojave. However, there exist remote sensing tools that reveal the true complexity of geomorphic surfaces, even when on-site fieldwork is not possible or desired. This study uses remote sensing as a simple way to test perceived homogeneity of the study area surface. Similar methods can be used for other sites in less accessible areas. Spatial and areal differences between a United States Geologic Society (USGS) geologic map and surface material classified from a remote sensing scene are compared through the use a Geographic Information System (GIS). It is important that the military and academicians correctly perceive the high degree of surface complexity that exists in desert areas and that may not be reflected visually or in routinely available and widely accepted material, particularly in those locations where on site work cannot be accomplished.

Study Site

The study site is located just north of Edwards Air Force Base and Rogers Dry Lake, the alternative landing site for the NASA space shuttle and home of the U.S. Air Force Test Pilot School (Figure 2-4). Dominated by alluvial fill, the area contains a

variety of landforms representative of the larger western Mojave region including bedrock knobs of basalt and more complex mineralogy, various alluvium, and small playas (Figure 2-1). It dips slightly in elevation from the northeast towards the southwest and drains toward Rogers Dry Lake. The temperature range is moderately large, averaging 37.4 degrees Celsius in July and minus 1.9 degrees Celsius in January at Lancaster, California, southwest of the study area. The diurnal temperature range averages 25 degrees C and relative humidities of less than 10% are common in the summer (Rowlands, Johnson et al. 1982). Selection of this particular study area is based on several criteria: inclusion of a wide range of surface geomorphic features representative of the larger western Mojave; imagery coverage availability; a surface area and corresponding image area of suitable size for data manipulation; and proximity of the location to such resource conflicts as mining, archaeological sites, and military training activities.

The U.S. Borax open pit mine is located along the eastern boundary of the study area and is near several paleoindian sites. A preliminary archaeological survey, requested and funded by U.S. Borax, was recently conducted as part of the Life of the Mine Project, which will eventually expand the area used to deposit mine tailings (W&S Consultants 2000). Despite the relatively small size of the survey area (2880 acres), 16 new archaeological localities were identified, all of which are prehistoric.

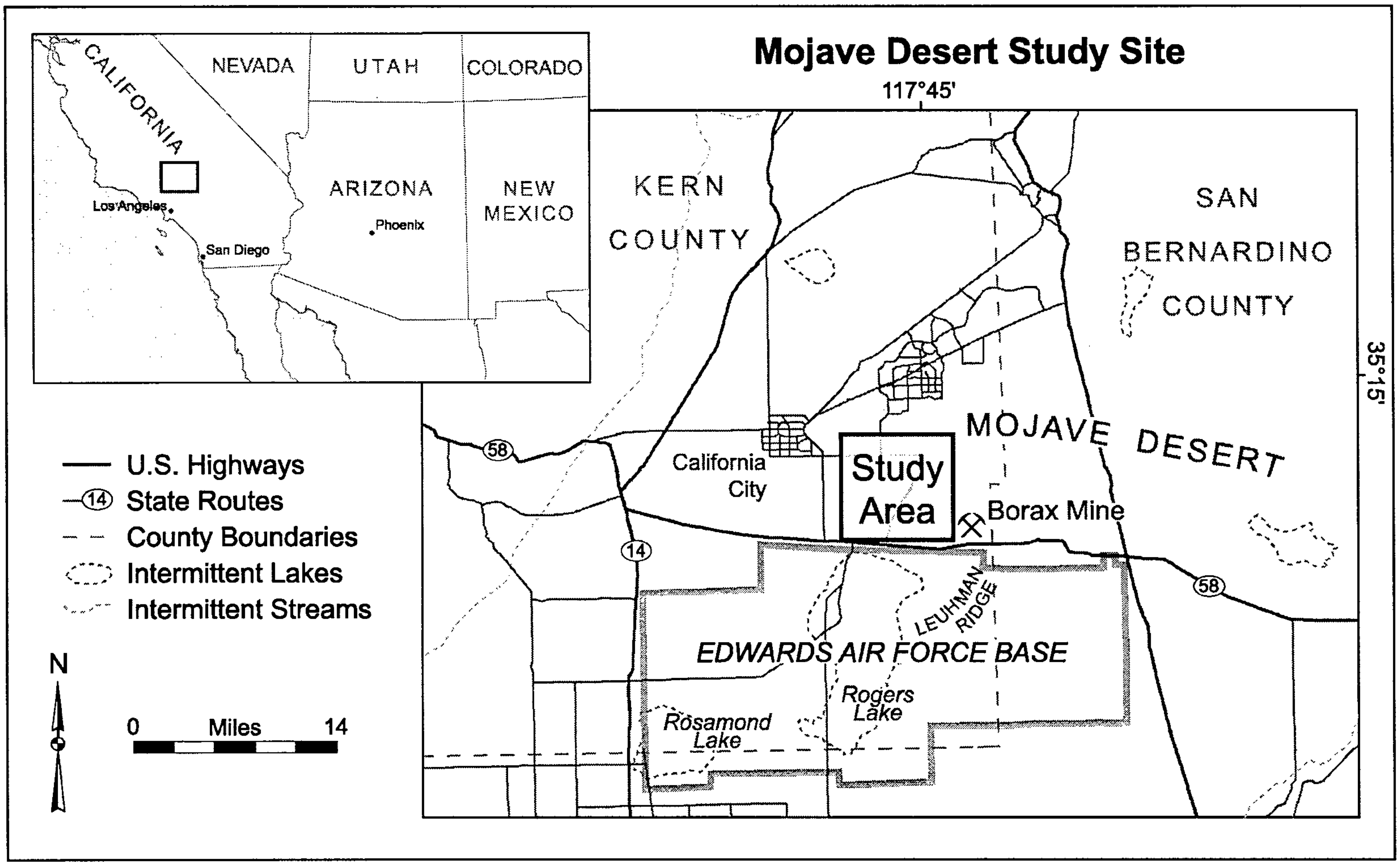


Figure 2-4. The study area is located north of Roger Dry Lake and Edwards Air Force Base in the western Mojave Desert, California. The Borax Mine is to the east.

Methods

Data Characteristics, Collection, and Preparation

Thematic Mapper Simulator (TMS): A valuable airborne sensor for the analysis of seemingly homogenous desert landscapes is the Thematic Mapper Simulator (TMS). Designed to simulate the Landsat Thematic Mapper (TM) sensor at a slightly higher resolution, TMS measures surface radiance in 11 discrete wavebands in visible and infrared portions of the electromagnetic spectrum. Seven of these bands correspond to LANDSAT bands 1-7 and four additional bands rest between LANDSAT TM bands. An additional band, Band 6, exists in both high and low gain modes, bringing the total number of channels for the TMS instrument to 12 (Table 2-1).

Table 2-1. TMS Bands and Wavelengths.

Channel	Wavelength Range (microns)	LANDSAT Thematic Mapper Equivalent Band
1	0.42 - 0.45 micrometers	equates to non-TM band A
2	0.45 - 0.52 micrometers	equates to TM band 1
3	0.52 - 0.60 micrometers	equates to TM band 2
4	0.60 - 0.62 micrometers	equates to non-TM band B
5	0.63 - 0.69 micrometers	equates to TM band 3
6	0.69 - 0.75 micrometers	equates to non-TM band C
7	0.76 - 0.90 micrometers	equates to TM band 4
8	0.91 - 1.05 micrometers	equates to non-TM band D
9	1.55 - 1.75 micrometers	equates to TM band 5
10	2.08 - 2.35 micrometers	equates to TM band 7
11	8.50 - 14.0 micrometers (low gain)	equates to TM band 6
12	8.50 - 14.0 micrometers (high gain)	equates to TM band 6

The TMS sensor is normally flown aboard a NASA ER-2 aircraft, the civilian equivalent of the USAF U-2 high altitude reconnaissance platform. TMS has a nominal instantaneous field of view of 1.25 mrads with a ground resolution of 25 meters per pixel when imaged at a height of 65,000 feet. The TMS scene used in this study has a 25 meter pixel resolution. The TMS line scanning device scans at a rate of 12.5 scans per second with 716 pixels per scan. The swath width is 15.4 kilometers when imaged at a height of 65,000 feet in altitude, while the scanner's field of view equals 42.5 degrees (NASA 1992). Minor atmospheric absorptions present in TMS data can be removed reliably using a standard Moderate Resolution Atmospheric Radiance and Transmittance (MODTRAN) atmospheric correction (Nowicki 1998).

TMS imagery was obtained directly from the National Aeronautics and Space Administration Research Center (NASA Ames), located at Moffit Field, California. TMS data are available at nominal cost from the United States Geological Society Earth Resources Observation Systems Distributed Active Archive Center (USGS EROS EDC DAAC) via the internet (http://edcimswww.cr.usgs.gov/pub/imswelcome/).

Base Map for Georectification: In order to facilitate GIS analysis, it is necessary to georectify data to a standard projection and datum. A digital line graph (DLG) of the road network in the study area was downloaded from the USGS to provide a base map (http://edcftp.cr.usgs.gov/pub/data/DLG/LARGE_SCALE/, accessed multiple times in October-November, 2001). The DLG is a vector based map at 1:24,000 scale, using the Universal Transverse Mercator (UTM) projection and the NAD27 datum. The

USGS provides DLGs in compressed, SDTS (Spatial Data Transfer Standard) format free of charge. WINZIP, a freeware file compression/decompression software package (available at http://www.winzip.com/ accessed numerous times in 2001) decompressed files. The files were imported into ERDAS Imagine, a widely available commercial software program designed for image processing. The SDTS formatted files were then translated into ERDAS Imagine format, which is compatible with ESRI's ArcGIS family of software. The USGS DLG serves as the reference image for georectification of the TMS imagery subset and the USGS geologic map.

USGS Geologic Map: Exhaustive search revealed that Dibblee (1967) has authored the only readily available published geologic map centered on the western Mojave Desert. Published in 1967, the map is a 1:250,000 scale UTM projection using the NAD27 datum (Dibblee 1967). Available only in paper format, it had to be digitized for import into a GIS and analysis. Evan Palmer, a graduate student in the Arizona State University Geography Department, enlarged the map by a 4:1 ratio and used a digitizing board to produce a vector overlay of the initial study area in UTM/NAD27 projection and datum. Using the VectorWarp extension to ESRI ArcGIS software, he then rubbersheeted the digitized overlay to the USGS road network DLG base map.

Image Processing

Processing of the TMS imagery begins with translation of the remotely sensed data into a format compatible with the image processing software, and with a correction

for atmospheric distortion. Video Image Communication And Retrieval (VICAR) software was used to accomplish these steps. VICAR is a NASA Jet Propulsion Laboratory (JPL) developed, UNIX based image processing program, designed to process multi-dimensional imaging data (California Institute of Technology 1995). In addition to file translation and display, VICAR also allows application of the MODTRAN atmospheric correction algorithm to remove atmospheric path radiance (Berke, Bernstein et al. 1989). The final result of this step in image processing is an image, corrected for atmospheric path radiance, and translated into ERDAS Imagine format (Figure 2-5).

Classification: The USGS geologic map provides spatial location of eight geologic classes in the study area. The remote sensing imagery is compared to the geologic map by analyzing the spatial distribution of similar classifications. Therefore, eight classes are used to conduct supervised, and then constrained unsupervised classification, of the TMS imagery subset using ERDAS Imagine software.

Imagery Georectification: Conducting georectification of the TMS imagery in two steps avoids introducing error from resampling. Resampling occurs each time an image is referenced and it may affect the spectral integrity of the data (Schrader and Pouncey 1997). Initially, the raw TMS subscene was georeferenced to the USGS

Figure 2-5. Raw TMS image, with MODTRAN atmospheric correction algorithm applied. North is to the right. The bright area to the left is Rogers Dry Lake and Edwards Air Force Base.

road DLG (UTM/NAD27) using a standard ERDAS Imagine subprogram. A signature file was created during this process containing the georectification algorithm. That signature file was then saved. Once the raw TMS subscene was classified, the previously saved signature file applied the georectification algorithm to the new, classified images. Resampling at this point avoids introduction of error from resampling before and after classifying. Only ten ground control points are required to perform a third order polynomial rectification algorithm as used here (Schrader and Pouncey 1997). However, 33 ground control points were used in this step to increase accuracy. Figure 2-6 summarizes data preparation steps.

Populating the GIS

The first step in populating the GIS is creating a 'theme' to serve as the base map. This process began by adding the USGS road DLGs to the GIS using the 'Add Theme' function of ArcView 3.2. The study site contains area covered by two adjacent USGS road DLGs corresponding to the North Edwards and California City USGS Topographic Quadrangles. Both DLGs were added, and then merged by means of the ArcView Geoprocessing Wizard. The TMS supervised classification image layer was then added. The overlay initially centered at least one screen length offset (tens of kilometers) from the roads theme indicating an error in coordinate system/datum configuration. Finding the error source proved difficult. The error was eventually corrected by completely reprocessing the raw TMS imagery.

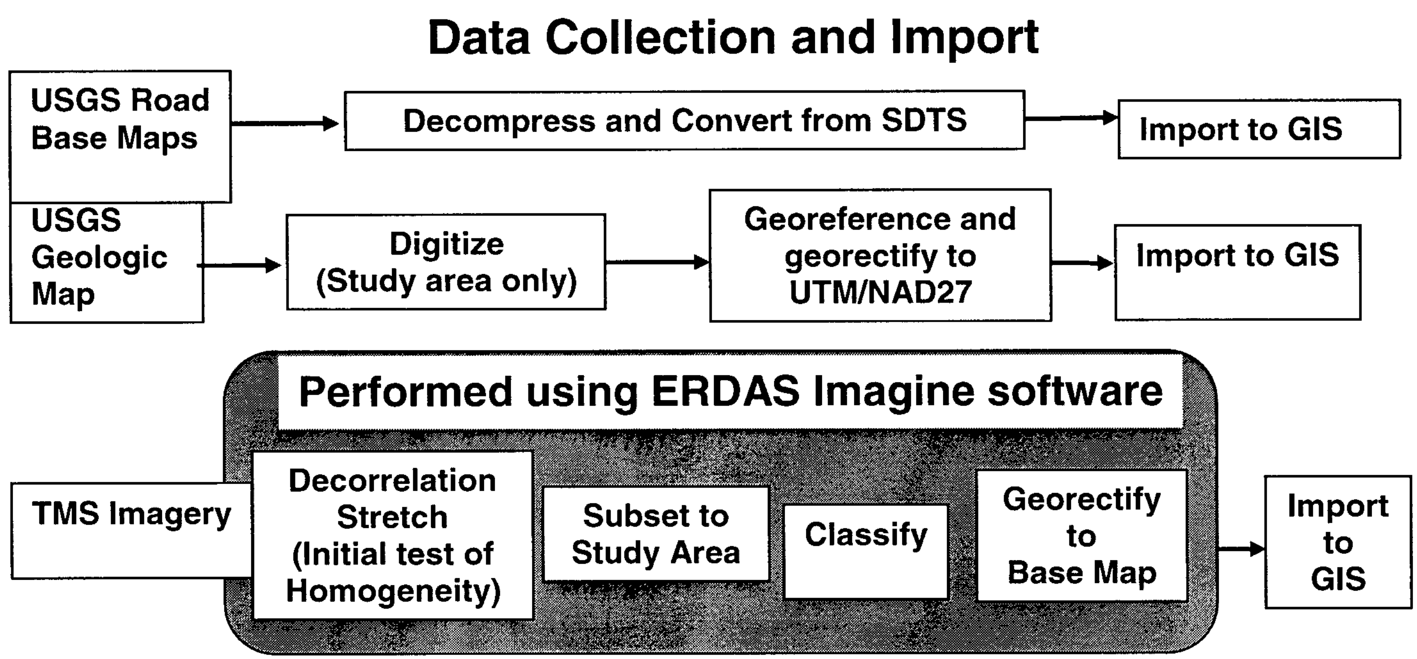


Figure 2-6. Data collected for this project came from low or no-cost sources. Manipulation is necessary to transform the data into workable format. Most imagery processing was completed using ERDAS Imagine, an image processing software package widely available at university level institutions.

Next, a union of the two road DLGs that already made up a single 'theme' in the ArcView project was performed. The 'merge' command fused all interior polygons in the theme, leaving only an outline polygon that corresponds to the boundaries of the study site. The ArcView 'Area of Interest' (AOI) thus generated was converted into a new 'theme' to provide a boundary for data imported into the GIS. Using the AOIborder, I then added and 'clipped' the digitized geology map using the Geoprocessing Wizard, added it to the 'view', and then set it up to serve as the 'mask' for all subsequent layers to be added. I discarded the AOI theme.

At this point, all layers (road base map, geologic map, TMS unsupervised classified layer, and TMS supervised classified layer) had been input into ArcView, converted to the UTM/NAD27 coordinate system and datum, aligned, and georectified and georeferenced. Finally, the geologic map was converted from vector form to raster. All layers were now in raster format to facilitate analyses. Last, a new field was created (nominal: 'class type') in the geology attribute table to allow for classification attributes to be added during analyses.

Sources of Error

The most significant errors introduced in this process are a result of the USGS geology map scale of 1:250,000. Comparing such a small scale map to the USGS road network base map (1:24,000) and the TMS image (1 pixel = approximately 25 m, for a scale of approximately 1:25,000) contains numerous problematic issues. A one millimeter error in digitizing the geologic map, for example, results in an error of 250

meters on the base map or 100 pixels on the TMS imagery. In addition, areal detail on the geological map is generalized in relation to the TMS image and the base map, making nuances in the larger scale overlays undetectable in the geologic layer. Another significant source of error is the decision to restrict the number of classes used in processing the TMS imagery to the geologist's units mapped by Dibblee (1967). Because there are only eight classes identified on the USGS geologic map, assumption of more than eight classes in the TMS imagery would invalidate comparative analyses. Table 2-2 summarizes sources of error, mitigation strategies, and provides a qualitative value of the effect.

Analysis

Data Check

An initial processing goal rests in determining if there are indeed significant differences between what could be discerned by field observation, the geologic map and remotely sensed imagery. Therefore, preliminary work involved conducting a decorrelation stretch of the TMS study area sub-scene. A decorrelation stretch enhances color differences in highly correlated data (Gaffey, McFadden et al. 1993). The process uses principle component analysis to transform data to the principle component coordinate system where the data contrast is enhanced. Data are then transformed again back to their original coordinate system for display. A TMS image was chosen to stretch initially, using band combination 3, 7, and 10. This band combination corresponds to

LANDSAT TM bands 2, 4 and 7 respectively, an optimal arrangement for arid regions that minimizes atmospheric scattering and maximizes lithologic color signatures and spatial resolution (Sabins 1997). Results of this preliminary analysis compared to the same area in ASTER (Advanced Spaceborne Thermal Emission and Reflectance Radiometer – another NASA remote sensing instrument) VIS/NIR (Visible/Near

Table 2-2. Sources of error.

Source	Mitigation Strategy	Qualitative Effect
Scale errors – USGS Geologic map at 1:250,000, USGS road network DLG at 1:24,000, TMS imagery at 25 m per pixel	Significant error is caused by generalization of the USGS geologic map and the digitization process. Evan Palmer enlarged the geologic map study area at a 4:1 ratio to digitize it, thus minimizing the effect.	USGS geologic map – significant USGS road Base map and TMS imagery – nominal
Subjective generalization of data: Selection of eight classes based on the number of USGS geology map classes	None	Moderate
Georectification error	33 ground control points were chosen to minimize RMS. The minimum requirement for a third order polynomial is 10 points. The high RMS (3.3) is a result of areas on the boundaries of the raw image that fall outside the boundaries of the study area. No ground control points were chosen in these areas. The regions were subsequently 'clipped' in ArcView (discarded), but the software does not support generation of a new, more accurate RMS at that point.	Small
Atmospheric absorptions, scattering and reflections effect radiation reaching TMS sensor	Apply the MODTRAN atmospheric correction algorithm.	Nominal
Surface variables influencing spectral signatures (presence of vegetation, human features, etc.)	Qualitative dismissal	Nominal
Reclassification errors	Avoided reclassification during rectification process	Nominal

Infrared) wavelengths and the USGS geologic map are shown in Figure 2-7. The apparent significant spatial variations and complexity of surface composition in the processed imagery justifies additional investigation of apparent heterogeneity.

GIS Analyses

The goal of these analyses is to extract spatial patterns that assess differences between the USGS geologic map and remote sensing overlays. In order to establish baseline information, an initial step quantified the surface area identified in the digitized USGS geologic map by surface type (Table 2-3 and Figure 2-8). This information represents basic data available to geomorphologists today. It shows that in this study area, there is a high proportion of alluvium, granitic fanglomerate, and fanglomerate. Next, I compared areas on the USGS geologic map layer with the supervised classified TMS layer. Both layers possess eight classes. The result of this analysis identifies differences in data between two layers (Figure 2-9). The total area classified by the geologic map layer as basalt, for example, can be compared to the total area identified as "Class 3" in the supervised classification of a TMS derived layer. The tabular output from this unique conditions analysis (Table 2-4) quantifies differences in total basalt area identified by these two methods.

I conducted the same type of analysis between the USGS geologic map overlay and the unsupervised TMS classified layer (Figure 2-10). Last, I produced an overlay

a.

b.

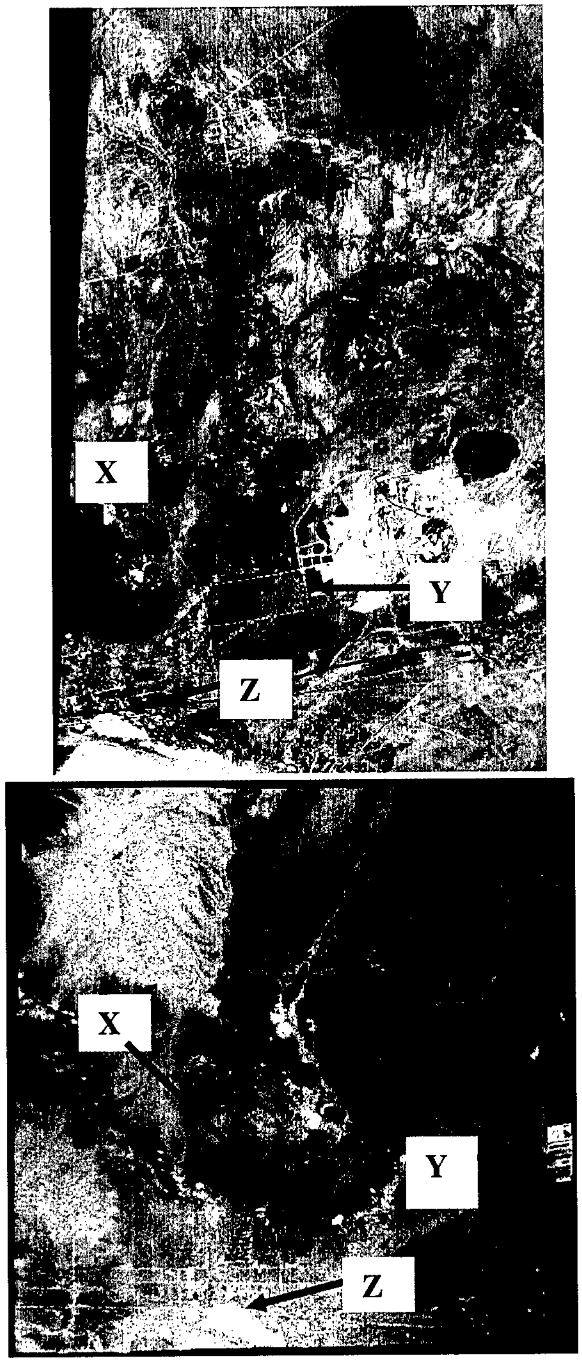


Figure 2-7. Comparison of ASTER image (a) in visible and near infrared wavelengths and a decorrelation stretch of the TMS image (b). Basaltic knobs correlate well between the two images, but the TMS image shows considerably more surface heterogeneity in areas of unconsolidated material.

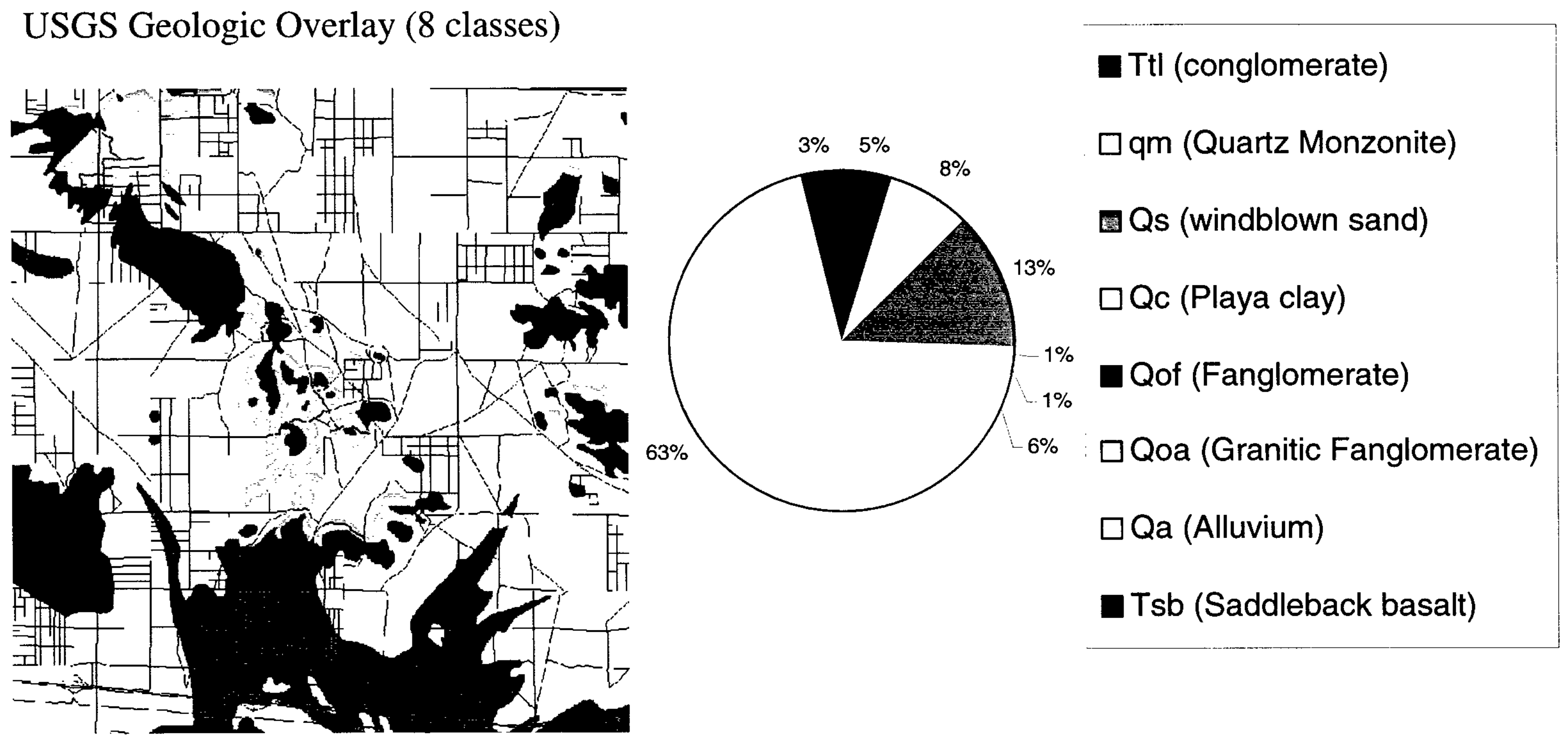


Figure 2-8. The digitized USGS geologic map (left, shown here overlain with the USGS road network DLG) is divided into 8 geologic classes (Dibblee, 1967). This classification system shows a preponderance of the study area (86%) as fanglomerate, windblown or fluvially deposited sediment. The geologic map is approximately 13.5 km in length and in height.

USGS Geologic Overlay (8 classes) (a)

Supervised Classified TMS Overlay (8 classes) (b)

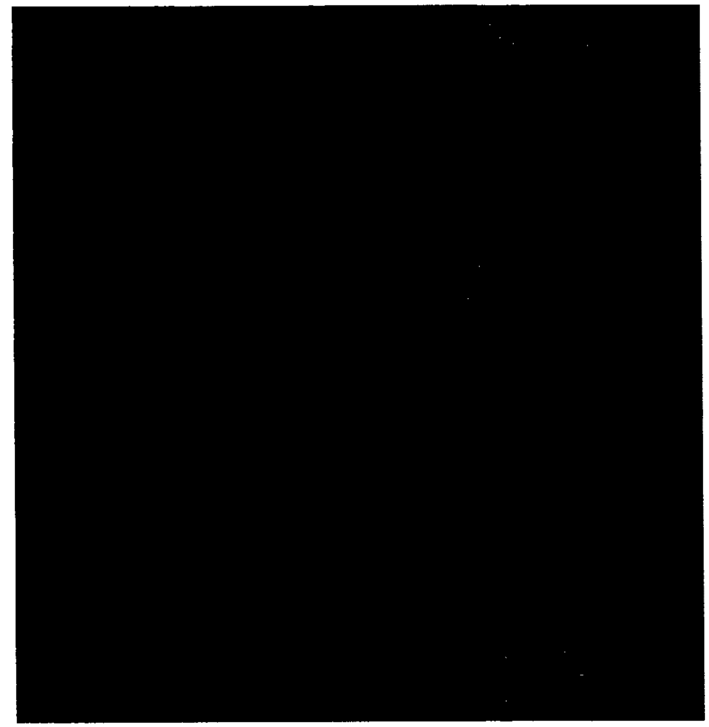
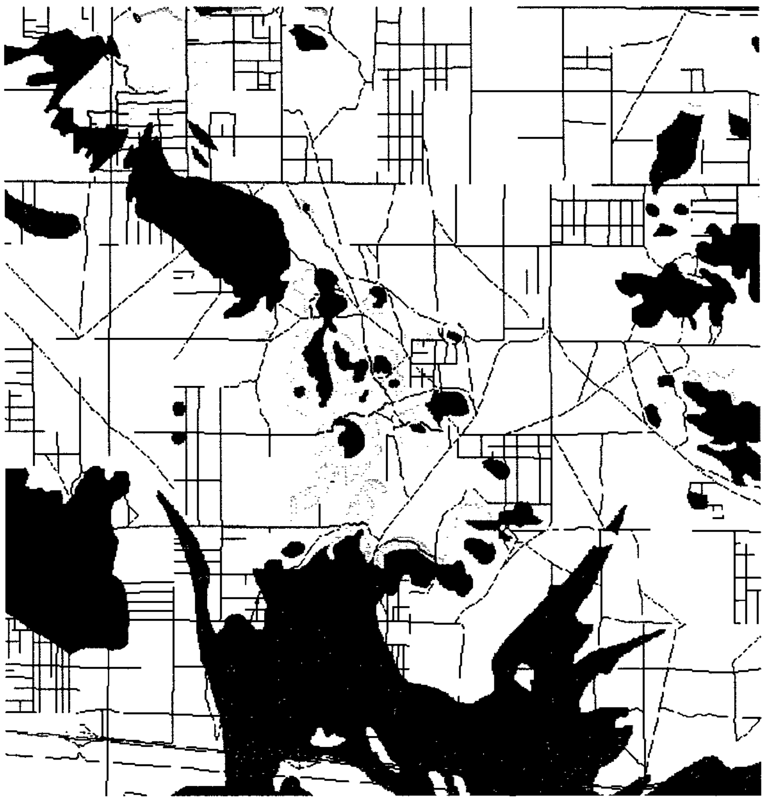


Figure 2-9. Comparison between the digitized USGS geologic map (a) and the supervised classified TMS image (b). The classified TMS image does not correspond well with bedrock outcrops identified in the geologic map, yet it shows considerably more heterogeneity in areas the geologic map identifies as alluvium or fanglomerate. Note: Image represents approximately 13.5 km ground distance on each side.

USGS Geologic Overlay (8 classes) (a)



Unsupervised Classified TMS Overlay (8 classes) (b)

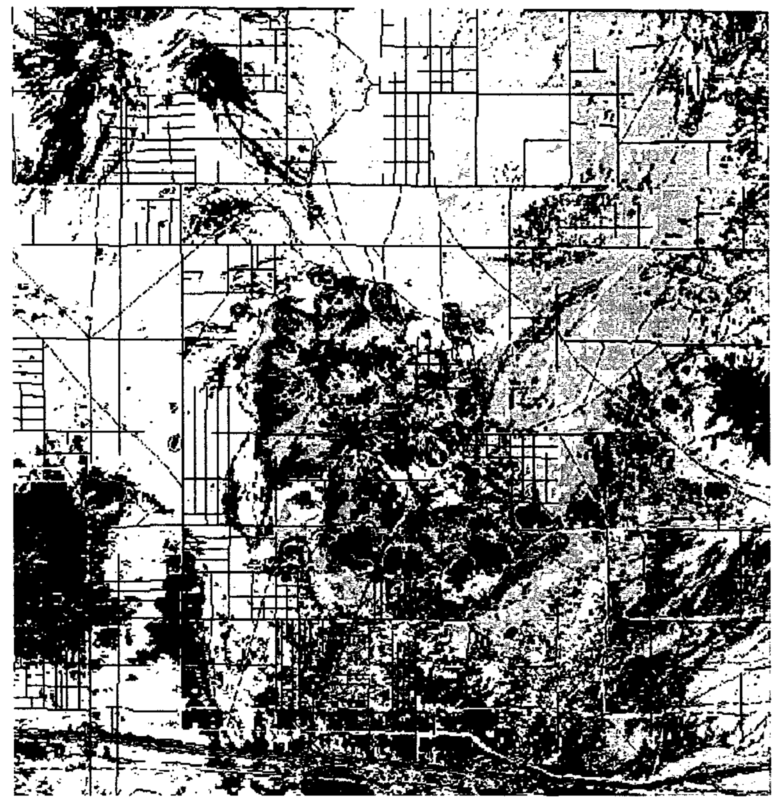


Figure 2-10. Qualitative correlations between and the geologic map classes (a) and TMS unsupervised classes (b) (based on spatial distribution) are apparent. Bedrock geology correlates particularly well. Note: Each image represents approximately 13.5 km ground distance on each side.

Table 2-3. Image area (defined in pixels) of the digitized USGS Geologic map, correlated with geologic class.

Class	Pixel Count	Geologic Class
1	21913	Tsb – Saddleback Basalt
2	32299	Ttl – Conglomerate
3	48338	Qm – Quartz Monzonite
4	82440	Qs – Windblown Sand
5	7529	Qc – Playa Clay
6	7565	Qof – Fanglomerate
7	39923	Qoa - Granitic Fanglomerate
8	388993	Qa – Alluvium
Total	629000	

Table 2-4. Results of a cross tabulation analysis between supervised TMS classes (rows) and USGS geologic map categories (columns). Quantities indicate pixel count. The largest number of pixels under a USGS geologic map category indicates the best correlation with a TMS class. TSB (Saddleback Basalt), for example, correlates well with TMS class 3.

Class	TTL	QM	QS	QC	QOF	QOA	QA	TSB
1	619616	217906	2600711	1303390	10404	111265	1011211	2890
3	4472853	276284	2595220	217328	60112	129761	14609817	4851443
4	3660763	9964431	10291001	388705	187561	7021833	14403182	119068
6	192763	1774749	2504763	92480	1162647	462111	27296339	991848
7	43061	77163	255765	2890	6936	118490	11305680	578
8	40460	363273	367030	10115	1445	593895	6386900	867
9	3468	247384	473093	289	738684	1734	4772546	135252
10	301427	1048492	4737577	160684	18496	3098658	32633302	230911

combining USGS geologic map with the unsupervised classified TMS layer. Using the ArcView map calculator, I multiplied the USGS overlay by the unsupervised classified TMS layer. The resultant map highlights the surface heterogeneity of the TMS layer and the authority of the standard USGS geologic convention (Figure 2-11). Figure 2-12 summarizes data transformations and analyses.

Figure 2-11. Combination overlay using information from the USGS geologic map and the unsupervised TMS classified image. This image clearly shows the heterogeneity apparent in the TMS imagery, yet classes correspond well spatially with the bedrock geology identified on the USGS map. Note: Image represents approximately 13.5 km ground distance on each side.

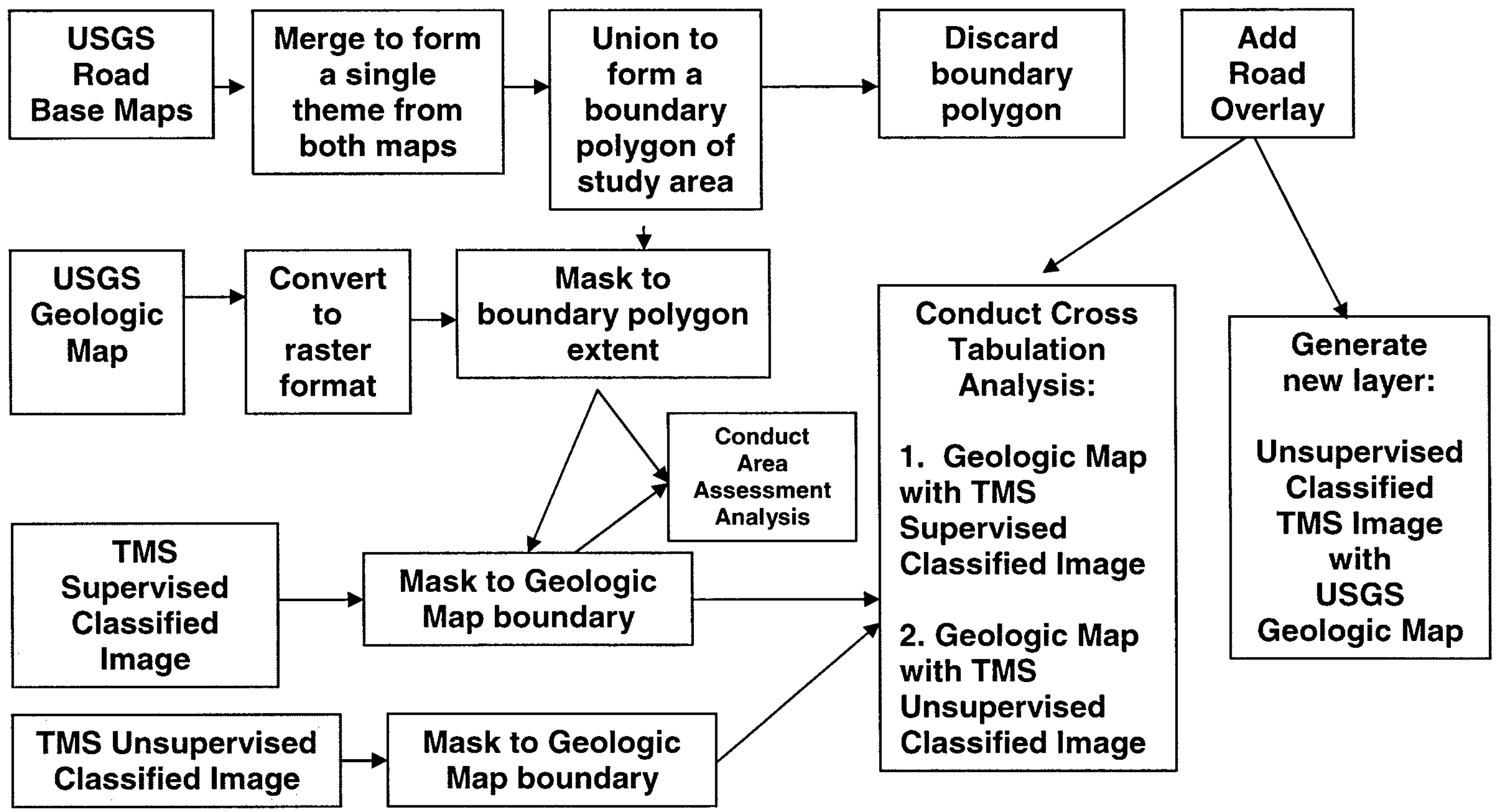


Figure 2-12. Simple area analysis and cross tabulation indicate a qualitative relationship between TMS imagery classes and the USGS geologic map classes. A GIS layer combining an 8-class unsupervised classification of the TMS image with the 8-class geologic map illustrates remarkable heterogeneity within alluvium, windblown sand and fanglomerate, yet maintains the core distribution of bedrock geology identified by the USGS.

Results

Initial analysis of the USGS geologic map layer shows a preponderance of the study area classified as alluvium, windblown sand, granitic fanglomerate, or fanglomerate - terms that are at best ambiguous in their ability to discriminate composition or depositional attributes of the landscape. The USGS map identifies 86% of the study area in these terms.

The unique conditions overlay that compares the USGS geology layer with the supervised classification TMS layer resulted in a more balanced output. Although it is speculative to associate Dibblee's geologic mapping with class types identified here, 59% of the surface area identified in this overlay corresponds to areas defined on the USGS map as areas predominantly composed of basalt or conglomerate. Significantly, only 41% of the surface area correlates to alluvium, windblown sand or fanglomerate.
A cross-tabulation analysis correlated the area of a designated class in the TMS image to each area in the USGS geologic map class. Good correlations infer a match of the TMS class to a geologic class defined by the USGS. The unique conditions overlay that compares the USGS geology layer with the unsupervised classified TMS layer also resulted in more balanced output. However, this overlay presents a more complex spatial distribution that does not lend itself to correlations between classes identified by the USGS geologic map and classes identified by the TMS image.

The final overlay (Figure 2-11) compliments the USGS geology map and also includes newly identified heterogeneity displayed by surface material captured in the

TMS imagery. It illustrates remarkable heterogeneity within the alluvium, windblown sand and fanglomerate, yet maintains the core distributions of bedrock geology identified by the USGS.

Discussion and Conclusion

The USGS geologic map reflects mid-20th century thought about the western Mojave Desert, exhibiting a disproportional area of undifferentiated alluvial fill, fanglomerate and windblown sand (Figure 2-1). This is not surprising since the USGS focused on mapping bedrock structure, not alluvium. Regardless, this 1967 map and its accompanying text (Dibblee 1967) are the only official USGS source identifying geology in the western Mojave Desert, and information such as this is a primary source that researchers traditionally use when investigating an area.

The homogeneous nature of the USGS geologic map and the visual monotony of landscape in the western Mojave leads to erroneous perceptions of regional geomorphology often reflected in the literature (Dibblee 1960; Jaeger 1965; Dibblee 1967; Boettinger and Southard 1995). Research findings can potentially affect environmental management decisions given extensive population and development pressures. Breaking the TMS supervised classification scheme into additional classes may provide a more accurate assessment, but information to base additional classifications upon is not available without field work. Therefore, with the information at hand, one cannot produce a supervised classified map that faithfully reflects reality. Furthermore, I consider the supervised classification overlay this project did produce as

unworthy of even qualitative assessment given the great disparity of spatial arrangement in some classes compared to the USGS geologic map which I consider to be generally correct, particularly where bedrock outcrops are indicated.

The problem is a 'catch-22' facing researchers and decision-makers who cannot or who do not take to the field. Many of today's desert maps are generalized, particularly in areas of likely future military operations, and the danger of misconception may affect more than simply research. The desert areas of Afghanistan, Iran, Iraq, the Sinai or North Africa for example, currently hold much more importance for accurate geomorphic assessment than does the Mojave. Those areas are not always open to field examination, and scholars and soldiers are at times, forced to make hypotheses with less than complete data. Recognition that these landscapes may be much more complex than anticipated may affect research, perceptions, and decisions. Understanding limitations of analyses using remotely sensed imagery is imperative.

At the same time, analysis of remotely sensed imagery does provide practical information that compliments widely available data. Analysis of the constrained, unsupervised classification of the TMS image in this study provides useful information. TMS classifications produced in this analysis cannot quantitatively be associated with geologic surface units faithfully because the discrete spatial patterns identified on the geologic map and the classified TMS imagery differ to some degree. However, it is possible to qualitatively match some TMS classes with geology based on spectral and spatial characteristics. This assessment is valid because the TMS data reflect surface areas that are distinct based on their individual spectral value. The supervised TMS

scheme is based on an average of many pixel values and therefore does not provide a valid assessment. The unsupervised TMS classification, therefore, despite being limited to only eight classes, provides some basis for qualitative assessments when coupled with the aid of the geologic map used as a guide for several specific geologic surface categories.

Despite the success of the unsupervised classification in displaying accurate distributions of surface geology, combining the information in the USGS overlay with the unsupervised TMS image can make a more accurate assessment. Areas of the resultant layer qualitatively associate with geologic classes in the USGS map. The more accurate spatial distribution provided by the TMS image results in a more accurate overlay than that portrayed by the USGS map alone. However, all classes in this overlay cannot be correlated directly to geologic types identified in the USGS map. The strength of the TMS imagery is that it breaks up the alluvium, fanglomerate and windblown sand classes of the USGS map into subsets that are more reflective of reality, but since these subsets do not correlate to information available in the USGS map, their makeup is unknown. Ground truthing of unsupervised classes then permits additional mapping.

The purpose of this chapter however, does not rest in producing an accurate surface geology map. The purpose is to test the hypothesis that the western Mojave Desert is as homogeneous as it appears to be visually and as it is depicted to be on the USGS geologic map. Clearly, the combined USGS/unsupervised classified TMS overlay demonstrates significant complexity and heterogeneity in surface material within the study area and also in the low-relief western Mojave. Trench excavations and fieldwork

in the study region (conducted as part of another study - see Appendix A) reveal substantial heterogeneity even within the area covered by a single 25 m resolution TMS pixel.

Complexity inherent in visually homogeneous desert regions is not always well perceived or understood. This study of a well-known desert in the United States that is easily accessible for research, demonstrates the degree of potential misperception. The complexity of reality is not well defined here, and that may affect local decisions regarding resource management, management of urban encroachment, an understanding of the tectonic activity in the region. However, misperception of desert areas that are not easily accessible and that can potentially become arenas for military conflict in the future, can have consequences many times more costly. Ultimately, misperception or poor understanding of the military operating environment can cost the lives of soldiers (see Chapter III). This study suggests there may exist a gap between common perceptions some people may have of desert regions and the complexity of reality. Accounting for the complexity of reality in desert hotspots around the world may be of significant importance to decision makers, especially in the applied realm of military geography.

CHAPTER III: THE DESERT ENVIRONMENT: A MODEL EXAMINING NON-TEMPERATE WARFARE ENVIRONMENTS

Introduction

A large proportion of the world's most powerful armed forces regard temperate climates with rolling, forested terrain to be normal fighting conditions (O'Sullivan and Miller 1983). Operations in non-temperate regions, such as the arctic, jungles, mountains, or deserts, challenge even the best-trained and equipped forces. Military success in unfamiliar regions requires knowledge of environmental conditions, special training, suitable equipment, and strong leadership.

The United States Army pays particular attention to unfamiliar, harsh operating environments because of the strategic importance these regions have to the National Command Authority and the nation. Unclassified applied military research aimed at overcoming environmental challenges is plentiful, but comparatively few publications consider physical geography as foundational information. Applied studies in military science treat physical geographic considerations such as climate, soils, vegetation, weather, and terrain as 'given' conditions, as opposed to dynamic processes that often affect the conduct of operations. The primary goal of applied studies is to deal with the effects of these geographic variables. Historical studies of battles and campaigns also often overlook militarily significant geographic aspects of conflict, choosing instead to concentrate on leadership, tactics and technology. Topical studies concerning warfare are by definition diverse, yet few works incorporate a geographic approach as key to understanding.

This chapter explores an alternative method of examining military operations in non-temperate environments. This research develops and assesses a heuristic conceptual model that synthesizes physical geographic information on non-temperate operating environments with the effects these conditions have on the conduct of modern ground combat. This model identifies key environmental parameters that influence the conduct of military operations. It analyzes the effects of these conditions and dynamic processes on troops, equipment, and tactics, providing empirical historical examples where possible. The robustness of this conceptual model is assessed in the context of harsh warm desert environments. If physical geography is indeed a key variable in military operations, it is critical to assess a coherent, understandable model useful for applied military science concerning military operations in non-temperate environments where many conflicts occur. The ultimate goal of a model that meets rigorous assessment is to provide an alternative, complementary regional analysis methodology that can act as a primer for thought to soldiers and others who may have future work in desert regions.

The study begins with a discussion of traditional approaches to the role of geography in relation to military operations in non-temperate environments. This review provides context and justification for pursuing this study. I then explain methods used to develop a conceptual model that emphasizes the influence of physical geography on military operations. Application of the model to desert environments then provides a means to evaluate the model.

Background

The ways to approach the study of military operations in non-temperate environments are as varied as the individuals conducting the analyses. Soldiers regard the subject as an applied science requiring an intimate understanding and use of physical geography knowledge to successfully execute missions under a wide variety of operating conditions. Military historians describe past conflicts, interpret equivocal facts, conduct critical analyses, and ultimately provide an evaluation of events with a goal of increasing understanding. Topical researchers approach military subjects in ways that are so diversified as to defy simple classification. Political, medical, moral, biological, psychological, or economic views of conflict for example, tend to evolve from paradigms each discipline embraces. Each of these approaches contains geographic components.

The importance of physical geography is clearly recognized in competent work concerning the execution of land warfare, particularly at the operational and tactical scales. Applied studies in particular, should contain a strong geographic component, as many works do; yet the geographic emphasis of countless applied studies in military science focuses on coping with the effects the environment has on military operations. Fundamental physical geographic aspects of the environment (those that explain why there are regional differences between temperate and non-temperate environments) are often treated as 'given' conditions and largely ignored in analyses.

The justification of this study rests in the assumption that misconception or poor understanding of physical geography is not conducive to full appreciation or

comprehension of the operational environment, or of the impact it has on military operations. All operational environments consist of complex and dynamic interrelationships. Military leaders need to understand the dynamics and basic effects of the environment, as well as reasons why those conditions exist and can change. History is replete with military disasters brought on by misconceptions or a poor understanding of the regional operational environment (Table 3-1).

The model proposed in this study is an alternative approach to applied works and is designed to complement the wide body of knowledge on non-temperate warfare. Doctrine, history, and a great variety of topical studies shape human perceptions of the environment, perceptions that may not be the same as environmental reality (Figure 3-1). Soldiers executing missions in these operating environments must make adaptations to tactics, techniques, and procedures (TTPs) to cope with these conditions. Consideration of fundamental and dynamic processes of the physical environment and the effects these variables have on military operations are essential to full understanding of the operational environment, and must be considered. This is not to imply criticism of any other approach or previous work, but an evaluation and consideration of geographic data provides users with more depth of knowledge to anticipate conditions in similar circumstances that may not be covered in doctrine or other official publications.

Table 3-1. A selection of famous military reversals resulting from poor understanding or misconception of physical geography processes active in the operating environment.

Date	Event	Comment Related to Dynamic Processes	Source
1274 & 1281	The Mongol leader Kublai Khan's invasion fleets bound for Japan were twice destroyed by Typhoons.	Kublai Khan did not anticipate storms that commonly form in the South Pacific and move through the Strait of Korea during particular seasons.	Winters *et al.* (1998)
1812	Napoleon and 600,000 troops marched into Russia on 23 June, but only 10,000 survived the subsequent retreat in winter.	Napoleon did not anticipate the vastness of Russian terrain nor the harshness or timing of the Russian winter.	Dupuy and Dupuy (1986) Winters *et al.* (1998)
1941	Hitler invaded Russia on 22 June with 3 million troops, 129 years after Napoleon. The Germans were defeated in large part because of the harsh Russian Winter.	Hitler misperceived Russian terrain and weather. Autumn rains created mud, crippling logistical support, and the Russian winter with –40 degree C temperatures caught the German soldiers in summer uniforms because they expected a brief campaign.	Dupuy and Dupuy (1986) Winters *et al.* (1998)
1943	Misjudgment of tides in the U.S. invasion of Tarawa in November 1943 led to the death of over 300 marines trying to get to shore from landing craft grounded on coral.	U.S. forces failed to properly consider strong tides and the depth of the inner reef, forcing Marines to debark 600 meters from shore and swim with full equipment under withering fire.	Regan (1987) Spiller (1992)
1991	Coalition troops surprised Iraq by conducting a flank attack across a featureless desert.	Failing to consider the impact of Global Positioning System technology, Iraqi forces believed the vast, featureless desert of the Al-Muthanna Province to be un-navigable and thus failed to secure their right flank.	United States Dept of Defense (1992)

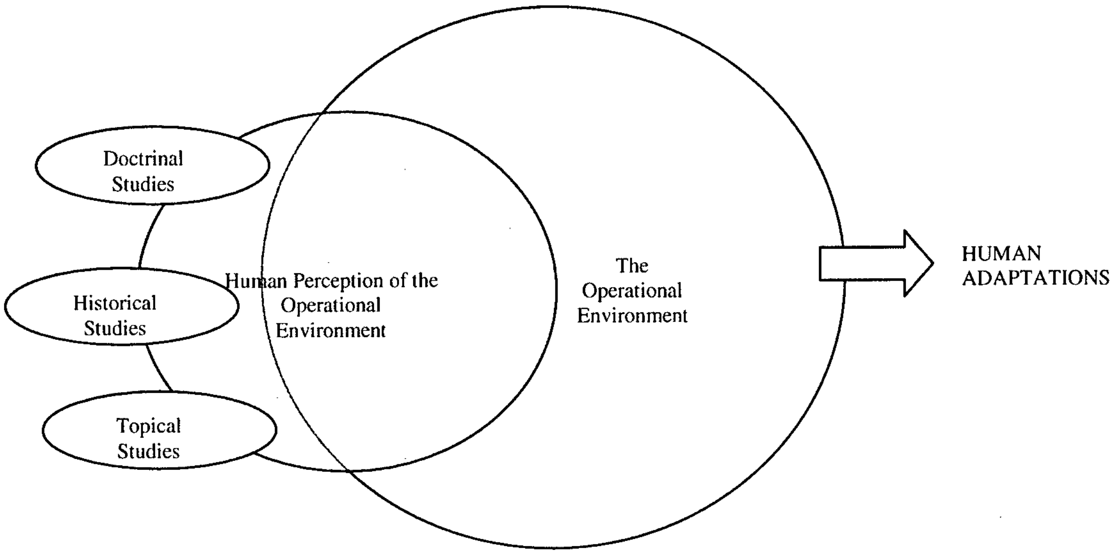


Figure 3-1. Human perceptions of non-temperate regions are shaped in part by doctrinal, historical, and topical works. These perceptions, exemplified in this Venn diagram, rarely assess the complex and dynamic reality of an unfamiliar operating environment accurately or completely.

Geography and Doctrine

US Army and Marine Corps land warfare doctrine are the official embodiment of applied studies in military science. Doctrine provides fundamental principles that guide military actions in support of national objectives (Department of Defense 2001). Army or Marine Corps Field Manuals (FMs) include ground warfare doctrine, and this guidance links to other official publications such as those furnished by the Center for Army Lessons Learned (CALL) (Deputy Chief of Staff for Doctrine 2001). Doctrinal publications are systematically organized from a military perspective to be easily understood and used by soldiers. As such, doctrinal emphases concerning operations in

non-temperate environments focus on identification of environmental effects and practical matters of how to cope with them, not an overall geographic perspective of dynamic processes. Table 3-2 shows primary FMs that address warfare in non-temperate regions, their systematic organization, and a qualitative assessment of their scope and allotment of space to the influence of physical geography.

Table 3-2. Scope of geographic influence in Army Field Manuals concerning non-temperate warfare.

Publication	Title	Chapter Organization	Devotion to Geographic Concepts	Character of Geographic Concepts
FM 3-97.6	Mountain Operations	4 Chapters: Intelligence; Command and Control; Firepower and Protection of the Force; Maneuver, Logistics and Combat Service Support	One chapter	Discusses the physical environment and its effects on personnel and equipment
FM 31-71	Northern Operations	7 Chapters: General; Operations; Combat and Combat Support; Combat Service Support; Communications; Other Tactical Operations; Training	Two sections of one chapter	Defines and describes the environment, and discusses general effects on operations.
FM 90-3	Desert Operations	4 Chapters: The Environment and its Effects on Personnel and Equipment; Preparations for Desert Operations; Operations in Desert Conditions; Combat Service Support	One chapter	Briefly describes and categorizes desert terrain. Discusses general effects of environment on operations.
FM 90-5	Jungle Operations	7 Chapters: The Jungle Environment; Life in the Jungle; Preparation and Training to Deploy to Jungle Areas; The Threat in Jungle Areas; Tactical Operations; Helicopter, Armor, Mechanized Infantry and Combat Support Operations; Combat Service Support	One chapter	Cursory description of environmental conditions such as climate and weather, terrain and vegetation.

Extensions of doctrine, such as CALL publications (Center for Army Lessons Learned 1990b), Battle Analyses (Simulation Training and Instrumentation Command 1991; Army Medical Department 2002) and Staff Rides (Robertson 1987), also contribute to formal military education, but devote comparatively little to geographic insight beyond discussion of terrain and perhaps weather during the conflict. The emphasis of most works in applied military literature rests on solutions.

Physical Geography and Military History

Soldiers, Noncommissioned Officers, and especially Officers in the U.S. Army are expected to expand their study of warfighting beyond doctrinal publications. The Army recognizes military history as an essential part of leader training and makes an effort to instill the desire to experience it in its leaders. The Army school system supports these efforts by requiring historical studies as part of the curriculum, as does officer accession components such as university Reserve Officer Training Corps (ROTC) and the Service Academies. Battle analysis, a formalized method of examining historical battles and campaigns, has long been a part of the curriculum in the Army Officer Education System (Simulation Training and Instrumentation Command 1991). Military units and the Army school system undertake staff rides to assist interpretations of historical battles. The Army maintains an official reading list for all leaders, from Cadets through senior leaders above the Brigade level, where historical works are prominent (Chief of Staff United States Army 2000).

Comparatively few works evaluating historical battles, campaigns and wars rely on the contributions of understanding physical geography as critical to understanding historical conflict. Many historical works consider leadership, tactics and technology as key themes. According to the United States Army Center for Military History, the institution responsible for recording and interpreting Army history, American military history "deals with the confluence and interaction of military affairs with diplomatic, political, social, economic, and intellectual trends in society" (United States Army Center of Military History 1989, 2). The Center for Military History records militarily significant events including the conduct of battles, campaigns and wars, the organization of armies, tactics and technologies used, and leadership, but rarely embraces the fundamental principles of physical geography and the effects these have on the conduct of military operations. For example, the Center for Military History refers to Douglas W. Johnson's seminal geographic works on World War I, *Topography and Strategy in the War* and *Battlefields of the World War, Western* and *Southern Fronts: A Study in Military Geography*, as being valuable, but unusual in approach (Jessup and Coakley 1982, 228).

Physical Geography and Topical Studies

Topical studies are publications written primarily to inform on a specific disciplinary interest, such as economics, politics, philosophy, and others. Topical studies considering military action are popular reading for both military and civilians. These varied works, in any number of disciplines, provide rich insight into warfare from a wide

variety of disciplinary perspectives and approaches. Unless the topic itself has a spatial component, comparatively few works emphasize the importance of geographic concepts. Fewer still incorporate physical geographic analysis.

Physical Geography and Military Operations

Doctrine, military history and military topical studies have been key components of military education since before the dawn of modern warfare. They have been continually refined and improved as time, tactics, technologies and paradigms changed to meet the needs of soldiers and scholars of the military art. To date, these efforts have been more than satisfactory in preparing our armed forces to cope with the varying and challenging environments of war. Regardless, U.S. Armed Forces continue to experience difficulty in operating in non-temperate environments because of poor understanding of regional geography. A cursory examination of challenges experienced during the Persian Gulf War in 1990-91 and in Afghanistan in 2001-03 reveals perplexing data that demonstrate a need for continued emphasis on geographic influences on military operations (Table 3-3).

Geographers recognize the need to continually educate Americans in geographic concepts with regard to military operations. John Collins, for example, recently argued that one of the issues he observed in his long and distinguished career in the Army was a lack of appreciation for geography (Collins 1998, xix). He felt compelled to write *Military Geography for Professionals and the Public* to provide a ready didactic source

Table 3-3. Some challenges experienced by U.S. forces during Desert Storm and Afghanistan caused by desert geographic conditions.

Physical Geography	Effect	Comment	Source
Vast, flat, open terrain	Made navigation and indirect fire accuracy difficult to achieve.	Excessive flat, open terrain traversed by Coalition troops in Saudi Arabia and Iraq during the 1991 Gulf War provided few terrain features suitable for navigation or accurate location information to direct movements and firepower. Military Global Positioning System (GPS) units that could accurately assess positions under these conditions were not widely available. Procurement of civilian systems alleviated some of the problems, but these systems required Selective Availability (a timing offset to prohibit enemy use of the system), to be turned off.	Gilewitch (1996) Suchan (2002)
	Increased engagement ranges over temperate environment	Open desert terrain in Iraq allowed tank engagement ranges in excess of two and one half miles, yet tank sights did not adequately allow target identification at these ranges. This shortcoming played a role in fratricide.	United States Dept of Defense (1992)
Hot, sandy ground, little shade	Stressed equipment not specifically designed for desert conditions	Hot temperatures in Saudi Arabia melted the insulation on WD-1, the standard issue communications wire used by U.S. and Allied Troops, rendering it useless without modification to employment.	Suchan (2002)
		Non-temperate lightweight boots in the Army inventory at the beginning of the Gulf Crisis were designed for use in the jungle. These boots are black and dark green, causing them to heat quickly in the desert. They are equipped with a steel shank in the sole to deflect bunji sticks, but the steel served to conduct heat to the foot in the desert. They featured water valves at the instep to allow water to drain rapidly from the boot after immersion, but these served to allow sand to enter the boot in the desert. While desert boots were quickly manufactured and issued, some troops never received them. In Afghanistan, desert boots designed for the Saudi Arabian sandy desert failed quickly in mountainous, rocky terrain.	Gilewitch (1996) Cox (2002) Cox and Cavallaro (2002) Suchan (2002)
		Desert Camouflage Uniforms (DCUs) were poorly designed initially, with reinforcing material in the crotch where body heat builds quickly and needs to escape. In the mountainous terrain of Afghanistan, after a redesign, soldiers complained about the DCU crotch seams ripping out.	Gilewitch (1996) Cox (2002)

of military geographic information to the media, military leaders, policy makers, educators, and concerned citizens (Collins 1998). The text provides an overview of the interaction of geography and the prosecution of war in terms that are understandable to any reader, and is therefore able to reach audiences that academic geographers do not. Winters *et al.*, (1998) examined connections between a number of historical military operations around the world with basic geographic components of weather, terrain, vegetation, climate and soils. Doyle and Bennett (2002) compiled proceedings from a conference on military geography, providing twenty case studies exploring the interplay between terrain and battle. Other scholars authored a variety of publications in the same vein (Johnson 1918; Johnson 1921; Jackman 1962; Peltier and Pearcy 1966; Jackman 1971; O'Sullivan and Miller 1983; O'Sullivan 1991; Underwood and Guth 1998; Palka and Galgano 2000; Ehlen and Harmon 2001; O'Sullivan 2001; Palka 2001a).

Perhaps the most telling information regarding a need for continued emphasis on the relationship between geography and military operations is the continuing demand for widely available, readable, unclassified geographic information on non-temperate regions. For example, shortly after the terrorist attacks at the Pentagon and World Trade Center on 11 September 2001, officers at the Military Academy realized that there existed no current, unclassified regional geography on Afghanistan. Adequate classified material was available on a need to know basis for those troops going into operations in the area, but others who may go in the future and still others who had reason to be interested in regional information had no readily available sources. Basic geographic information was simply outdated or not accessible. Within weeks, the Department of

Geography and Environmental Engineering at the Academy published a pamphlet, and later a CDROM, titled *Afghanistan: A Regional Geography* (Department of Geography & Environmental Engineering 2001a). This pamphlet filled the gap and was issued to all Brigade Commanders and above in the United States Army. It was extremely well received (King 2001; Palka 2001b). A subsequent publication entitled *Iraq: A Geography*, was published in early 2002 (Department of Geography & Environmental Engineering 2002) and another entitled *North Korea: A Geographical Analysis* was published in early 2003 (Geography Faculty 2003).

Despite the availability of vast amounts of quality material available on non-temperate warfare, there exists a continuing need for basic geographic information in an unclassified format to be available to a wide audience. The assumption of this chapter is that research founded in geographic principles provides rich insight to military practitioners and others not predisposed to consider the complex effects the environment may have on operating in unfamiliar regions. Unclassified examination of environmental realms such as the desert makes information widely available to troops anticipating harsh work in the region, allowing better training in preparation for units and individuals.

Methods

The goal of this study is to develop and assess a conceptual framework that incorporates the relationship between the physical geographic aspects of a non-temperate region with military operations. Although this model might be useful for a variety of operating environments, I use the desert environment to assess this approach. The model

provides an alternative, complementary method to understand varying effects of non-temperate operating environments. Figure 3-2 provides a visual depiction and context for this model. While historical and topical studies have a great influence on human perceptions of operating environments, the soldier is most concerned and influenced by U.S. Army doctrine, the official publications that are designed to guide soldiers' tactics, techniques, and procedures (TTPs). Doctrine helps shape human perceptions that influence expectations, preparations, and at least initial actions in unfamiliar regions.

The reality of the operating environment is multifaceted and does not always reflect preconceived notions. It is a complex milieu of interrelationships between dynamic processes and conditions of climate, soils, terrain, weather and vegetation (Peltier and Pearcy 1966). These relationships and conditions differ substantially between regions. Indeed, physical realms are often defined by these differences (Clark 1988).

Soldiers make adaptations in TTPs to fit these regional differences and these solutions are then channeled as feedback into doctrine through FMs, CALL publications, staff rides, professional journals, After Action Reviews (AARs), and other means. The focus of these feedback types rests on solutions – how to cope with differing conditions in differing operating environments. In turn, changes to doctrine based on this feedback affect soldiers' perceptions of the region.

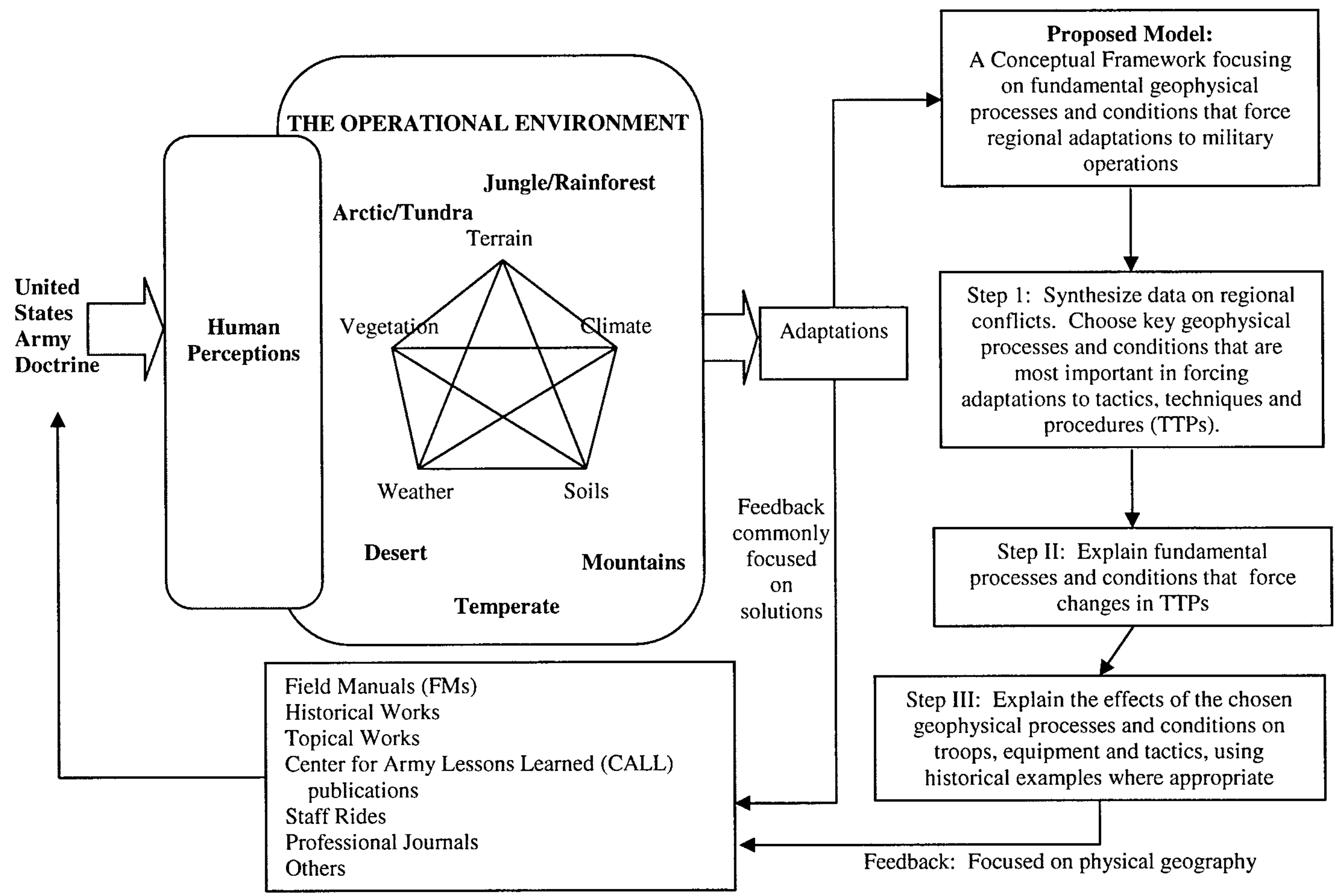


Figure 3-2. Diagram showing the relationship of the model proposed in this study to traditional feedback systems. The proposed model provides complementary, alternative feedback that emphasizes the influence of physical geography

The model proposed in this research, like other feedback mechanisms, is based on human adaptations to differing operating environments. However, instead of focusing on solutions, the model stresses fundamental factors that force regional adaptations in order to provide a more thorough understanding of predictive effects. This level of understanding provides more depth of knowledge that may allow soldiers to anticipate complex conditions and dynamic interrelationships that make up the reality of the operating environment in unfamiliar realms. Understanding these relationships may alleviate misconceptions that can have catastrophic effects in combat.

The type and number of adaptations to operating environments are complex and nearly infinite, so it is necessary to constrain this effort to key conditions and dynamic processes that have major effects on military operations in a particular environment. Understandably, these key factors differ in each environmental region, but the process to determine them remains the same. As illustrated in Figure 3-2, the initial step is to identify critical aspects of a particular operating environment that alter or constrain military operations. A wide body of literature exists to provide a database of information. It is not possible to consider all literature relevant to a particular region, and the choice of data is left up to the user. The criterion for selection of these topics therefore depends on the investigator's experience, interests, and knowledge, which suggest that different users of the model may emphasize different topics. This is purposeful. Individual creativity allows the model to be flexible enough to meet various user requirements. A soil scientist may emphasize geophysical factors that impact heavily on military trafficability, for example, whereas a climatologist may emphasize the dynamics of storms,

precipitation, or dust. The model is constructed to accommodate differing interests, needs, and depth of investigation.

Once these critical aspects of the operational environment are identified, the researcher then provides fundamental geographic information regarding the processes and conditions that govern these aspects in the region under study. This is a key component of the model, as this information is often not addressed in many data sources. The effects these processes and conditions have on military operations are then evaluated systematically by considering their impact on troops, equipment, and tactics. The use of historical examples is important to assess the relevance of geophysical processes and conditions chosen. Historical events provide vicarious and invaluable lessons that provide understanding to the present and guidance for the future (Jessup and Coakley 1982). They validate the data.

In order to assess this model, I apply it to harsh, warm desert environments that have often been the operating environment of U.S. ground forces, particularly in the last decade. In order to determine a pattern of geophysical processes and conditions that influence modern military operations in the desert, I reviewed doctrinal publications including FMs, CALL newsletters, various historical works and professional journals regarding modern operations in desert environments (including the Gulf War of 1991; the series of Arab-Israeli conflicts; the North African Campaign of World War II; the Iraq-Iran War; the Soviet-Afghanistan conflict; and the recent U.S. incursions in Afghanistan). I also considered personal and colleague experience in desert operations. After several iterations, I determined that the majority of key environmental issues could be logically

grouped under four geophysical factors: hydrology; aeolian processes involving wind and dust; insolation and temperature; and the character of desert terrain (topography). I believe these four factors adequately capture the majority of key conditions in the desert environment that make operations there distinct from the more familiar, temperate regions.

I then reviewed these four factors from a geographical perspective – are they different in desert environments than they are in temperate environments? If so, why? This basic geographic information is what seems to be missing from most applied studies. Once I established these parameters, I sought a systematic way to relate them and their effects to military operations.

Using an approach that is similar to that found in some FMs, I evaluate the influence of these geophysical factors on troops, equipment and tactics in modern warfare. While not a universally accepted stratagem for military audiences who prefer BOS (Battlefield Operating Systems) or METT-T (Mission, Enemy, Terrain, Troops, Time) analyses, this approach is user friendly to both military and civilian audiences and generates from geography as opposed to a military science aspect, thus providing an important, if not popular, perspective. I intentionally keep the analyses general and avoid discussion of solutions as these are well documented in doctrinal publications and some historical studies.

The next section of this chapter exemplifies how this conceptual approach can be applied to the analysis of desert warfare. It begins with a short argument for the importance of a geographic approach, and then broadly describes the desert environment,

causes, and global distribution. A more detailed analysis of the dynamic nature of the four chosen geophysical factors follows with explanation of the major effects these factors have on troops, equipment and tactics operating in the region. The conclusion assesses this model as complementary to other approaches to non-temperate warfare works.

Physical Geography and Military Operations in the Desert Environment

Deserts are relatively bereft of population and centers of power, yet a surprising number of important battles take place in arid and semiarid regions (Table 3-4). Strategic resources and religious and ethnic clashes are the primary causes. Deserts host such a large number of conflicts because they exist along routeways between continents (O'Sullivan 2001); they often form the boundaries between conflicting cultures; and in the Middle East, they contain a great deal of the world's oil resources. Future conflict is certain to occur in desert regions involving armies accustomed to temperate environments. This likely includes U.S. Armed Forces.

Understanding the dynamic nature of physical geography processes in deserts or any harsh, non-temperate environment is key to successfully anticipating and preparing for regional challenges. Task-based information is important, but it is rarely sufficient to

Table 3-4. Examples of arid and semiarid region battles that transformed world history, modified from Davis (1999).

Battle	Date	Forces Engaged	Importance
Meggido (Armageddon)	15 May 1479 BC	Egyptian – 10,000 Kadesh Alliance – Unknown	1st recorded battle in history; reestablished Egyptian dominance in Palestine
Beth-Horon	Oct 66	Roman – 30,000 Infantry 6,000 Cavalry Jewish – 14,000 light infantry	Unexpected Jewish victory incited general uprising in Judea
Badr	15 Mar 624	Medina – 300 Mecca – 900	Mohammed's victory against Mecca confirmed his authority as leader of Islam
Jerusalem	9 Jun – 18 Jul 1099	Crusader – 1,250 Knights, 10,000 Infantry Muslim – 20,000	Crusader victory marked the high point of European attempt to control the Holy Land
Hattin	4 Jul 1187	Crusader – 1,200 Knights, 18,000 Infantry Muslim – 18-20,000	Ended European domination of the Holy Land
Tenochtitlan	26 May – 13 Aug 1521	Spanish/Allied – 86 Cavalry, 118 Crossbowmen, >700 Infantry, 50,000 Tlaxcalan allies Aztec – Unknown	Capture of Aztec capitol marked the end of the empire and Spain became the dominant force in Central America for the next 300 years
Ayacucho	9 Dec 1824	South American – 5,780 Spanish – 9,310	Marked the end of Spanish rule in South America
San Jacinto	21 April 1836	Texan – 783 Mexican – 1,500	Led directly to Texas independence
Mexico City	19 Aug – 14 Sep 1847	U.S. – 7,200 Mexican – 16,000	Caused collapse of Mexican government and the end of the Mexican-American War
Tel El Kebir	1882	British – 17,401 Egyptian - 22-25,000	British victory established control over Egypt and Suez Canal
Israeli War of Independence	14 May 1948 - 7 Jan 1949	Jewish – 30,000 active, 30,000 reserve Arab – 39,000, +50,000 untrained Palestinians	Established the State of Israel
Desert Storm	24-28 Feb 1991	Allied Coalition – 665,000 Iraqi – 350,000	Denied control of substantial oil reserves to Iraqi dictator Saddam Hussein

train troops fully. How to cope with heat in the desert, for example, is difficult to explain without some knowledge of how hot it may become, when it is hottest, and why. Anticipation of similar environmental conditions in various regions of the world can provide advantages to forces that are prepared, and can be disastrous to their opponents.

The unique physical landscape of desert regions presents a variety of environmental challenges to military ground forces that differ significantly from those of temperate environments. Desert aridity for example, makes the location, availability and quality of fresh water sources of paramount importance to military forces. High intensity insolation and hot temperatures with strong diurnal changes challenge both troops and equipment. The ferocity of hot desert winds and accompanying ubiquitous dust wreaks havoc on equipment and can stop military operations altogether at times. The unique character of desert terrain with its scarcity of vegetation and long-range visibility has tremendous impacts on tactics. In the following sections, I discuss each of these geophysical factors, investigating their dynamics and examining their effects on troops, equipment and tactics in desert operations, illustrating issues with historical examples.

The Desert Environment

Human perception of desert terrain is often inaccurate, and generally relates to an area that is desolate, hot, and preferably sandy (Abrahams and Parsons 1994). In reality, deserts (from Latin, *desertis*, barren or deserted) may not be any of those things. Numerous scientific definitions have been based on a variety of criteria including

drainage patterns (de Martonne and Aufrere 1927), erosion processes (Penk 1894), climatic criteria based on vegetation types (Koeppen 1936), on potential evapotranspiration (Thornthwaite 1948), and on vegetation types alone (Shantz 1956). A widely used classification system developed by Meigs (1953) and adapted by UNESCO (1979) targets aridity (Table 3-5), and provides an exceptional illustration of desert locations worldwide (Figure 3-3).

In addition to aridity, a key aspect of desert terrain that characterizes the environment and has significant impact on military operations is a lack of continuous vegetative cover. Aridity or low temperatures are primary reasons (Mabbutt 1977). However, human actions can turn areas in temperate climates into virtual deserts. In the mid 1930s, the Great Plains of Kansas, Oklahoma and Texas experienced deflation and soil erosion that reached disastrous proportions following a great expansion of wheat cultivation (Heathcote 1983). Along the fringes of desert core regions, the risk from human action is even greater. In Sahelian North Africa, for example, demand for firewood resulted in the elimination of most trees and large shrubs, and overgrazing removed most grasses and small shrubs. A long drought beginning in the 1960s exacerbated the situation, creating extreme land degradation in one of the poorest

Table 3-5. UNESCO Aridity Index. P is annual precipitation, ETP is the mean annual potential evapotranspiration, based on the Penman formula (UNESCO 1979).

Subhumid Zone	$(0.50 < P/ETP < 0.75)$
Semi-Arid Zone	$(0.20 < P/ETP < 0.50)$
Arid Zone	$(0.03\ P/ETP < 0.20)$
Hyper-Arid Zone	$(P/ETP < 0.03)$

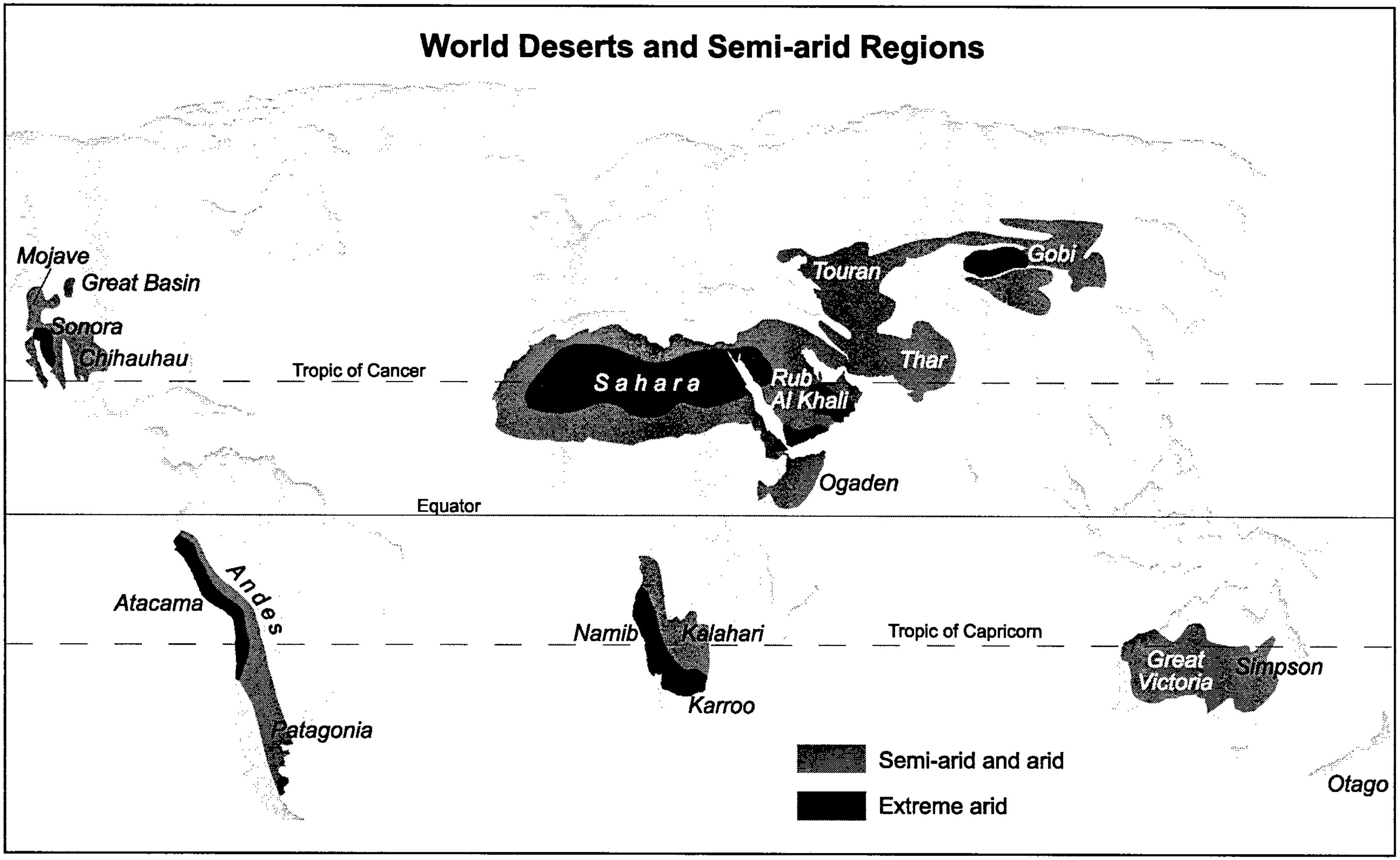


Figure 3-3. A map of arid and semiarid regions of the world based on Meigs' classification system. .

regions of Africa and effectively expanded the size of the desert (Thomas and Goudie 2000). Regardless of the cause, without a protective canopy of vegetation and the binding effects of root networks, a blanket of moisture retentive soil cannot accumulate on slopes. Erosion accelerates, soil cover is lost, and a wide variety of desert landforms can be created regardless of other environmental influences. Military implications of such conditions are numerous, including long-range observation and direct fires, good trafficability, and large areas of operation.

Desert Distribution and Causes

Deserts are widely distributed throughout the world and are occupied by human cultures historically in conflict. Deserts occupy approximately 11,500,000 square miles of continental land masses (Stone 1968), or approximately 20% of Earth's land surface (Figure 3-3). They exist on all continents except Europe. From a climatic standpoint, all desert regions are areas where precipitation is significantly less than potential evapotranspiration, causing the surface to be dry (Hartman 1994). However, desert temperature and precipitation regimes may differ substantially, which provides the potential to delineate a great variety of desert types. For the purposes of this discussion, I focus on only two major types of deserts: low latitude deserts, and midlatitude deserts.

The aridity commonly associated with desert regions is caused by a variety of atmospheric circulation mechanisms (Hartman 1994). Five climatic controls that create arid conditions are generally recognized. The first is the character of large-scale atmospheric circulation. The majority of hot and dry low latitude deserts lie between 20-

35 degrees north and south of the equator. It is here that the earth's atmosphere is dominated by dynamic anticyclonic high pressure – the descending limb of the Hadley Cell – that is inimical to the generation of precipitation (Lutgens and Tarbuck 1995) (Figure 3-4). These subtropical highs (STH) control atmospheric conditions, causing atmospheric subsidence accompanied by adiabatic warming and low relative humidity (Hidore and Oliver 1993), inhibiting convection, cloud formation, and precipitation. Low latitude deserts affected by these conditions extend to the west coast of all continents in these latitudes, but subsidence is weaker on the eastern sides of the subtropical highs and, with the exception of North Africa, which is sheltered by the Arabian Peninsula, aridity does not extend to the eastern coasts. Low latitude deserts are most extensive in North Africa, Arabia and the Middle East and Australia, and include the Sahara, the Mojave, the Sonora, the Rub Al Khali, the Great Victorian, the Kalahari, and others (Figure 3-3).

The presence of a topographic barrier such as a high mountain range between a moisture source and a desert region is the second climatic control that promotes aridity (Figure 3-5). As moist air blows into a topographic barrier, it is lifted and cooled adiabatically. Water vapor condenses out and some is lost as precipitation. On the leeward side, air sinks and warms, causing a region of aridity known as a 'rain shadow.' The rain shadow effect is partly responsible for desert areas just west or east of major mountain ranges such as Patogonia, in the lee of westerlies as they strike the Andes Mountains, and the Peru Desert, which lies in the lee of the easterlies in South America.

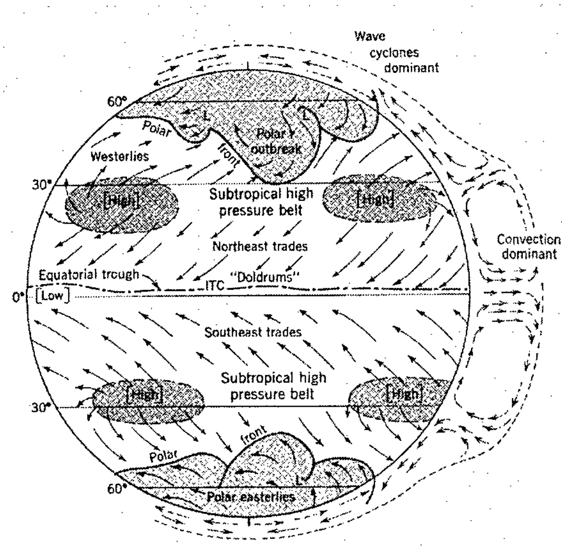


Figure 3-4. The Subtropical high pressure zone dominates atmospheric conditions 25-30 degrees north and south of the equator. This band of descending air is the result of Hadley Cell circulation, shown in this diagram as the large circular patterns of airflow bracketing the equator (Strahler and Strahler 1994).

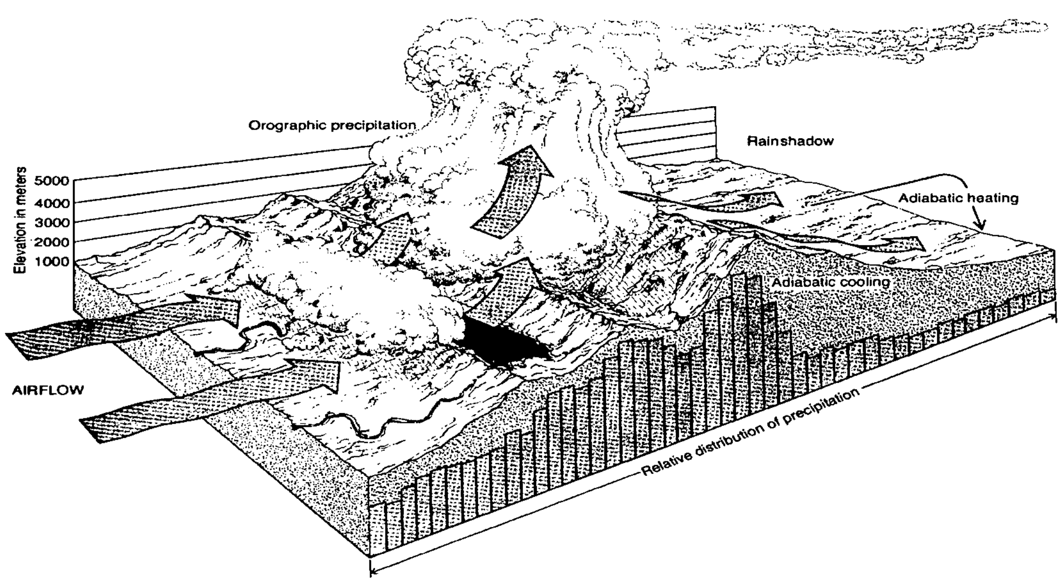


Figure 3-5. Orographic uplift causes precipitation on the windward side of mountain ranges, but as air descends the leeward side, it warms adiabatically and becomes stable, producing a rain shadow effect that promotes arid surface conditions (Marsh 1987).

Other midlatitude deserts including the Great Basin in the United States, the Otago in New Zealand, and portions of Central Asia on the leeside of the Himalayas, are also dry because of rain shadow effects.

An interesting subset of low latitude deserts is the West Coast desert. A primary cause of this desert type is a third climatic control, the upwelling of cold waters from ocean currents running parallel to the west coast of continents (Table 3-6). Cold ocean waters upwelling from depth by influence of persistent surface winds, cool low altitude air, which inhibits its ability to hold moisture and, more importantly, makes the air mass stable. Air stability refers to the propensity of an air mass to rise. Stable air does not rise spontaneously, so it stays at a relatively constant volume and pressure and does not provide opportunity for adiabatic cooling. It is not normally associated with cloud formation or precipitation. Land areas that fall under the influence of these stable atmospheric conditions remain arid.

West Coast deserts are often characterized by fog that advects inland from the west (Critchfield 1983). Again, upwelling cold water is key to this condition. Relatively

Table 3-6. Cold-water ocean currents create air mass stability that causes arid conditions along the west coast of continents. The four major cold ocean currents that are associated with desert conditions are shown here, after Critchfield (1983).

Region	Ocean Current	Desert
Lower California and Sonora	California	Baja California
Coastal Peru and Chile	Humboldt or Peru	Peru and Atacama
Northwest African Coast	Canaries	Sahara
Southwest Africa	Benguela	Namib

moist marine air that advects over cold upwelling currents is chilled to dew point resulting in the formation of fog. Thermal lows over deserts and prevailing winds can move this fog over arid lands, and it can be extensive, as in Baja California. However, the moisture from advection fog remains suspended in the atmosphere, largely unavailable to vegetation or anthropogenic use. Once the sun warms the land surface, radiant energy warms the atmosphere and the fog dissipates.

A fourth climate control that supports aridity is the distance that a region may be from a suitable source of moisture. The Gobi Desert in China and Mongolia is the largest midlatitude desert, characterized as cold and dry. It lies in the interior of the largest continent (Eurasia), far removed from moisture sources.

A fifth cause of deserts is airflow that is parallel to the coast, rather than on-shore. Somalia, for example, experiences a persistent wind flow that is parallel to the coast. Without an on-shore flow working in concert with orographic uplift, chances for rainfall diminish commensurately. The Atacama Desert in northern Chile and southern Peru exemplify a desert that is the result – in different times of the year and different locations – of four of the five factors. The persistent subtropical high influences the southern Atacama, while the Andes rainshadow influences the northern Atacama. Cold water and airflow parallel to the coast influence the entire region, except during El Nino-Southern Oscillation events that bring torrential rains when air pressures in the South Pacific reverse.

Desert Characteristics with Regard to Military Operations

The diversity in deserts is enormous, and local conditions are often considerably different even in areas commonly viewed as similar (see Chapter II, this dissertation). Regardless, low and midlatitude deserts do share common environmental factors that influence combat operations in both desert environments. Several of these are so onerous that they merit particular attention. Hydrology, aeolian processes, local radiation balance, and the unique nature of desert terrain greatly influence what can and cannot be accomplished in this harsh environment. In the following sections, I examine the particular characteristics of each of these factors and discuss how they influence military operations.

Hydrology

Human perception of desert conditions is likely to include recognition of aridity relative to temperate environments. Indeed, viable sources of potable water are perhaps the most important environmental consideration for military forces involved in desert operations. Both human and equipment demand for potable water increases substantially in dry climates. Fresh water is ultimately derived from rainfall that enters rivers, aquifers, and to a limited extent, lakes and ephemeral streams, but desert rainfall is often meager, irregular and unreliable. A reasonable view is that low latitude deserts average less than 20.5 cm (8 inches) (Fairbridge 1968).

When it does rain in the desert, storms are often violent (Walton 1969) and the desiccated surface (except in sandy tracts) is relatively impermeable to water, thus producing rapid surface runoff and attendant capacity for erosion and transport of surface material (Goudie and Wilkinson 1977). Table 3-7 illustrates desert precipitation variability by comparing humid and desert locations. Variability is expressed by the equation:

$$\text{Variability (\%)} = \frac{\text{the mean deviation from the average}}{\text{the average}} \times 100$$

Arica, Chile in the Atacama Desert is an extreme example, but illustrates this point well. This area experiences the world's lowest average annual precipitation at 0.08 cm (0.03 inches) and endured a 14 year period with no rainfall (Riordan and Bourget 1985). On another occasion, associated with an El Nino Southern Oscillation event, Arica received 100 mm (4 in) of rain in one day (Scott 1992).

High variability in rainfall often results in heavy, short term precipitation that causes flash flooding in wadis where cover and concealment exists, and washes out roads

Table 3-7. Comparison of the variability of rainfall between locations representing humid and desert regions (Goudie and Wilkinson 1977).

Location	Variability
Rome, Italy	14%
Central Sahara Desert	80-100%
Libyan Sahara Desert	> 100%
Dakhla, Western Sahara	150%

that the military logistical system depends upon. Infrequent heavy rains tend to run off the surface of deserts instead of seeping into the soils because the soil is ill prepared to receive moisture (Goudie and Wilkinson 1977; Scoging 1989). A rather large proportion of desert surfaces is impermeable to percolating water because of a vast amount of exposed bedrock (Cooke, Warren et al. 1993) and duricrusts (Nettleton and Peterson 1983; Watson 1989; Dixon 1994b). Desert soils are relatively unbroken by vegetation or a great deal of biotic activity (Cooke and Warren 1973; Cooke et al. 1993). Since vegetation in deserts is generally not sufficient to restrict loose sediment, running water has a tremendous capacity for changing surface morphology, often in a short time (Goudie and Wilkinson 1977; Scoging 1989). These conditions offer unique, and perhaps unexpected challenges to armed forces operating in these regions.

Potential Desert Water Sources: A direct result of the scarcity, irregularity and unreliability of desert rainfall is that reliable fresh water sources are not plentiful in the desert and those that do exist are not easily exploited for military use. The most reliable freshwater sources in the desert are exotic streams that perennially carry water from more humid regions through desert lands, such as the Nile in Egypt, the Tigris and Euphrates in Iraq, and the Colorado in North America. Most of these rivers have been dammed to control flooding downstream and to create reservoirs to provide reliable water sources and electrical power, such as the Aswan Dam on the Nile River that created Lake Nasser in Egypt and Sudan. While rivers and reservoirs are exceptionally good sources, their military use is limited to areas within the capacity of the logistical system to carry bulk

water from the source to consumers, the current level of water salinity and pollution, the potential susceptibility to poisoning, and the vulnerability of the dams themselves to destruction.

A second potential freshwater source in desert environments is groundwater. Useable groundwater is derived from rainfall or the seepage of freshwater lakes and streams into aquifers beneath the land surface (Figure 3-6). It may be available to military forces through springs or seeps in bedrock lithology, known as oases in the Middle East. The locations of oases in deserts are usually well known, having been discovered by early travelers and used for hundreds or even thousands of years, and consistently exploited by military forces. Despite the presence of oases, reliable military use of groundwater in modern times is primarily made available through drilling of wells that tap into underground aquifers as was done with great success during the North African Campaign in World War II (Toppe 1952) and during the Persian Gulf War in

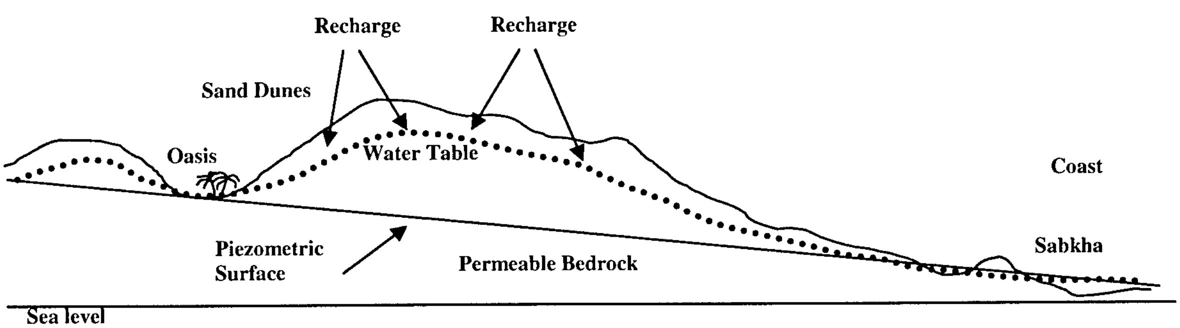


Figure 3-6. Diagram of principle features of groundwater in desert regions.

1991 (Knowles and Wedge 1998). In addition to the need for specific geological information to determine suitable drilling sites, the value of groundwater for military use is also limited because of its typically high variability in quality and salinity (Walton 1969; Goudie and Wilkinson 1977; Heathcote 1983).

Another source of fresh water that may be available for military use is found in ephemeral streams. Ephemeral streams, or wadis, fill with water for a limited period following a rain event. The vast majority of desert streams are ephemeral. All of the wadis studied in the study area discussed Chapter II, for example, are not perennial nor intermittent (seasonal), but can fill with water following a rain event. The military usefulness of ephemeral streams is limited because systematic collection is difficult to organize in the short duration of the stream's existence. The rapid flow rates of this water, coupled with the preponderance of loose sediment on the land surface, causes flowing water to experience high competence and capacity (Laronne and Reid 1993). It is therefore, heavy in sediment and other impurities, complicating its use by armed forces.

Finally, potable water for military use may also be available through processing of saltwater in desalinization plants. This high cost method requires a great deal of energy and is limited in location to coastal areas where ocean water sources exist and the significant, fixed location infrastructure has been built. The world's largest desalinization plant is located in Saudi Arabia and uses nearly 19 million liters of sea water a day (Collins 1998). It provided a necessary supplement to local and imported

water sources for Coalition Troops during the Persian Gulf War in 1991 (United States Dept of Defense 1992).

Water Quality: Natural water quality in deserts is highly variable and tends to be saline (Hills 1966; Goudie and Wilkinson 1977). Water is known as the 'universal solvent' because of its capacity to effectively dissolve a tremendous variety of materials. In desert environments where water input is limited, rainwater is exposed to large proportions of salts concentrated in surface sediment. Once in contact with water, these materials rapidly dissolve, making desert waters saline (Table 3-8). In some locations, high mineral content may simply make the water unpalatable and give it an unpleasant odor, but if concentrations are high enough, the water may be unsafe to drink for an extended period of time without treatment (Center for Army Lessons Learned 1990b). Variation in water quality in a given desert location can be dynamic with seasonal or severe stress in supplies (Hills 1966). U.S. Armed Forces can deploy Reverse Osmosis

Table 3-8. Water salinity characteristics (Goudie and Wilkinson 1977).

Water salinity (Parts per million total dissolved solids)	Type
35,000	Sea Water
3,000	Maximum potable level for human consumption
< 500 – 700	Recommended potable level for humans
Up to 1000	Quality of drinking water used by a single German Brigade in North Africa vicinity El Alamein in 1942 (Toppe 1952)

Water Purification Units (ROWPU) with troops in desert regions to purify local water (Association of the United States Army 2002), and these units normally provide on-site treatment to water derived from military wells (Baehr 1998).

Desert Water and Troops: Limited water sources and poor water quality significantly constrain military operations in deserts. Desert environmental conditions exacerbate these challenges and historically cause a great number of casualties not associated with enemy action. Troops require water largely for three reasons: to hydrate themselves; for personal hygiene; and for cooking. Salt water is unsuitable for any of these uses, so fresh water must be made available. In temperate environments, water is plentiful and troops can augment, if not completely satisfy their needs using fresh water available locally. Lakes, rivers, streams, and public water supplies are usually sufficient to support operations, but in arid desert regions, this is not the case. Fresh water supplies are limited and carrying fresh water to where it is needed is a logistical burden. Because of high temperatures and excessive physical strain that military operations requires of humans, troop water consumption increases significantly when operating in the desert. Temperate region water consumption for troops is estimated at 7.6 liters (2 gallons) per man per day (Center for Army Lessons Learned 1990a). In the desert environment, water consumption on average increases 4.5 times to nearly 34 liters (9 gallons) per man per day (Center for Army Lessons Learned 1990a). When physical activity increases, water consumption increases accordingly. A loss of two fluid quarts (2.5% of body weight) decreases efficiency by 25% and fluid loss of 15% of body weight is usually fatal (Center

for Army Lessons Learned 1990a). Loss of fluids may result in heat cramps, heat exhaustion, or heat stroke, all of which cause casualties.

Disease as a result of inadequate hygiene (which necessitates water) historically caused more casualties in desert warfare than enemy action (Cloudsley-Thompson 1993). Drinking unpotable water results in dysentery and diarrhea, while malaria, typhoid, typhus and scurvy are other diseases historically affecting armies in desert regions and directly related to the absence of water. Over half of the first brigade of German troops deployed to North Africa during World War II were sick with dysentery from drinking unpotable water, and from a lack of water to properly bathe (Toppe 1952). The Soviet Union experienced similar problems during their ten years in Afghanistan (Grau 1998). Despite advances in efficiency and water transport capability, the same problem faced U.S. troops during Desert Shield/Storm. LTC (then CPT) Suchan of the 101st Air Assault Division, spent seven months in the region, but only had an opportunity to use proper shower facilities seven times (Suchan 2002).

Requirements for potable water in deserts challenge the military logistical system. Water is difficult to carry. One gallon of fresh water weighs 17.6 kg (8 lbs) and takes up .38 cubic m (231 cubic inches). Because it is not often readily available in desert theaters of operation, the military logistical system must carry it from source areas to distribution points. This may include bulk breakdown from 5,000 gallon tanker trucks to 600 gallon water trailers and 5 gallon cans, or even distribution in 1 liter plastic bottles. Such a burden necessitates additional transport not normally organic to deployed units. During Operation Desert Shield for example, MG Pagonis, the principle U.S. logistician in the

Gulf War, was appalled to learn that XVIII Airborne Corps alone would need billions of gallons of water over the first few months in theater (Pagonis and Cruikshank 1992). Transportation requirements for this amount of water is staggering. The transport of fuel and ammunition during conflict usually has priority over water, often making the problem even more severe.

Exacerbating transport challenges for water in the desert are storage limitations driven by high temperatures. The optimum drinking temperature for water is between 10 and 15 degrees Celsius (50-60 degrees Fahrenheit) (United States Army Armor School 1993). Warm water is unpalatable and leaders find it difficult to keep soldiers properly hydrated when cool water is unavailable. This may lead to increased numbers of heat injuries because water consumption is the best prophylactic for these cases. If water is allowed to warm to over 92 degrees F, the production of bacteria dramatically increases, causing otherwise potable water to become an instrument of dysentery and diarrhea (United States Army Armor School 1993). Table 3-9 illustrates the relatively short storage life for water in small containers in a desert environment.

Table 3-9. Storage life for water in desert environment (United States Army Armor School 1993).

Storage method	Expected Storage Life
Metal 5 gallon cans	24 hours
Plastic 5 gallon cans	72 hours
Water trailer	5 days

In summary, environmental conditions in deserts increase the need for water consumption, yet reliable water sources are not plentiful and water quality is often quite variable. These conditions have historically caused excess casualties in desert warfare. Despite advances in technology, these challenges remain unsolved and will likely continue to confront troops operating in these environments in the future.

Water and Equipment: Like troops, military equipment is also susceptible to the limited and variable water quality common to desert regions. Many military engines are water cooled, and need reliable quality fresh water. Even potable water from desert wells and oases is usually high in mineral content, particularly salts (Hills 1966). These minerals corrode radiators and engine blocks and cause blockage in hoses and couplings as they precipitate out of solution. Engine related maintenance problems increase 50% in desert environments, causing a huge logistical burden (Center for Army Lessons Learned 1990b) not experienced in most other operating environments.

The Influence of Water on Desert Tactics: Key terrain is defined as any location that, when controlled, represents a significant advantage for one side over the other (Department of Defense 2001). Because water is scarce in deserts, source areas of potable water become key terrain. This changes the character of desert warfare significantly from that of temperate regions. In pre-modern warfare, routes for military movement in deserts were from one reliable water source to another. Armies not accustomed to desert operations or leaders without experience, often fell victim to water

shortages. Historically, water has often influenced or has been used as a force multiplier in desert military actions (Table 3-10).

All tactical movements are constrained by trafficability, or the difficulty with which it is possible to move over terrain. In general, trafficability is good in the desert, but there are exceptions. Sand can bog down vehicles, especially wheeled vehicles. Wadis create cross-compartment terrain with steep banks of unconsolidated material. Sharp angular rocks puncture tires and wreck havoc on footwear (Cox and Cavallaro 2002). The addition of water to the landscape however, has the most significant and immediate effect on military trafficability in the desert.

Terrain that supports vehicular traffic when dry can turn into a muddy morass when wet. Sand and gravel sized particles in desert sediment are relatively large and maintain substantial pore spaces that allows water to infiltrate well. Silts, and especially clays, retain water causing poor drainage and excessive runoff. A particular clay type known as montmorillonite (named after the town of Montmorillon in France and also known as smectite) has a layered structure of thin microcrystals. These crystals are not tightly bound, so water and even organic compounds are easily drawn into the cleavage planes between the layers, causing them to expand like an accordion and increasing the clay surface areas several fold. Thus, montmorillonite clays are strong water absorbers and swell considerably when wet, exhibiting high plasticity and cohesion (Hillel 1998). Desert sediments with significant smectite content are heavy when wet and reduce trafficability proportionally. Salt marshes of the clay-rich Qattarra Depression,

Table 3-10. Examples of desert conflict where water influenced actions.

Date	Parties Involved	Description	Source
circa 523 BC	Persians, Egyptians	The invading Persian army sent a strong force from Thebes to Kharijo (Kharga) Oasis and captured it, but the entire force perished before reaching water at the Oasis of Amon (Siwa)	Cloudsley-Thompson (1993)
1187	Christians, Muslims	A Crusader army of 21,300 infantry and cavalry attempted to relieve the garrison at Tiberias in present day Israel. Foolishly, they marched 25 km without water in hot July temperatures, and then made a dry camp at the Horns of Hattin. The Muslim army under Saladin surrounded them during the night. Mad with thirst, Crusader infantry attempted to break out toward Lake Tiberias, but were destroyed. Most of the remaining troops surrendered or were killed.	Duncan and Opatowski (1998) Watson (1995)
1798	French, Egyptians	Napoleon Bonaparte sent Desaix's division from Alexandria, Egypt to El Rahmaniya by the most direct route across the desert instead of a circuitous route along the Nile. They were ill prepared with temperate uniforms and insufficient water in the baggage trains, and suffered greatly.	Herold (1962)
1948	Arabs, Israelis	Arab forces cut off West Jerusalem's water supply in first Arab-Israeli war.	Wolf (1995; 1997)
1980-1988	Iran, Iraq	Both sides use diverted water to flood enemy positions.	O'Ballance (1988) Plant (1995)
1988	Angola, South Africa, Cuba	Cuban and Angolan forces launched an attack on Calueque Dam via land and then air. Considerable damage was inflicted on the dam wall and the power supply to the dam was cut. The water pipeline to Owamboland was also destroyed.	Meissner (2000)
1982	Israel, Lebanon, Syria	Israel cut off the Beirut water supply during its siege.	Wolf (1997)
1991	Iraq, Kuwait, US	During the Gulf War, Iraq destroyed much of Kuwait's desalination capacity during the retreat.	Gleick (1993)
1993-present	Iraq	To quell opposition to his government, Saddam Hussein poisoned and drained the water supplies of southern Shiite Muslims, the Ma'dan.	Gleick (1993) American University (Inventory of Conflict and the Environment ICE), (2000)

for instance, were made famous during World War II because they prevented penetration into the interior of the continent for Axis and Allied forces battling along the coast (Toppe 1952; Dupuy and Dupuy 1986; Gordon 1987; Perrett 1988). 'Sabkhahs' (saline flats underlain by silt, clay and sand and often encrusted with salt) were also of great concern during the Persian Gulf War in 1991 because of their treacherous trafficability (Knowles and Wedge 1998).

Infrequent, but characteristically heavy desert rains tend to collect in wadis and other low-lying areas that are attractive positions for forces in conflict as they often provide the only cover and concealment available. The relationships between rainfall and runoff are extremely complex, but flash floods in desert ephemeral streams exhibit three common characteristics: a rapidly rising bore that precedes peak discharge by only 10-23 minutes; quick floodwater recession; and extremely short lived flood events – often measured in hours from initiation to dry bed (Reid and Frostick 1989). Flash floods are a danger to troops and equipment in wadis, even if the rain falls some distance from their location. Rain tends to flow rapidly through desert wadi systems and can destroy units in the way with little warning. Rainwater also collects in other low areas where trails are often located and where soldiers are trained to operate, with attendant impact on trafficability. Water in southeastern Tunisia's Wadi Zigzaou, for example, blocked a British advance during the Battle of Mareth (Collins 1998). During the German retreat from El Alamein in 1942, a Panzer unit became stuck in mud after a sudden rainstorm and the tanks eventually had to be blown up to avoid their capture (Toppe 1952).

Radiation Balance

Insolation is the intensity of solar radiation incident upon an area of the earth's surface at a specified time interval (Thomas and Goudie 2000). The amount of insolation potentially available at any location on the earth's surface is determined by earth-sun geometry (Figure 3-7), but the amount of insolation actually reaching the earth is also a function of atmospheric conditions (Figure 3-8). Insolation travels through less atmosphere when the sun angle is high, allowing less atmospheric interference and subsequent weakening of energy as it moves toward the earth's surface. Low and midlatitude desert regions experience relatively constant high-energy insolation year-round.

Of particular vulnerability to heat are troops in armored vehicles. However, soldiers constantly in direct sunlight are susceptible to a myriad of deleterious effects from insolation exposure as well as high temperatures. Deserts experience some of the highest insolation rates of any location on the earth's land surface. Low atmospheric moisture over desert regions produces few clouds to shade the surface and reflect or scatter insolation (Oke 1993). The scarcity and character of desert vegetation provides little shade for surface material. Skies are clear about 70% of the time over desert areas; in the summer, that rate can exceed 90% (Mabbutt 1977).

The inequality in energy balance from high insolation rates causes surface temperatures in deserts to be unusually high. Virtually all the radiant energy absorbed by the desert surface must be dissipated as sensible heat because evaporation is almost

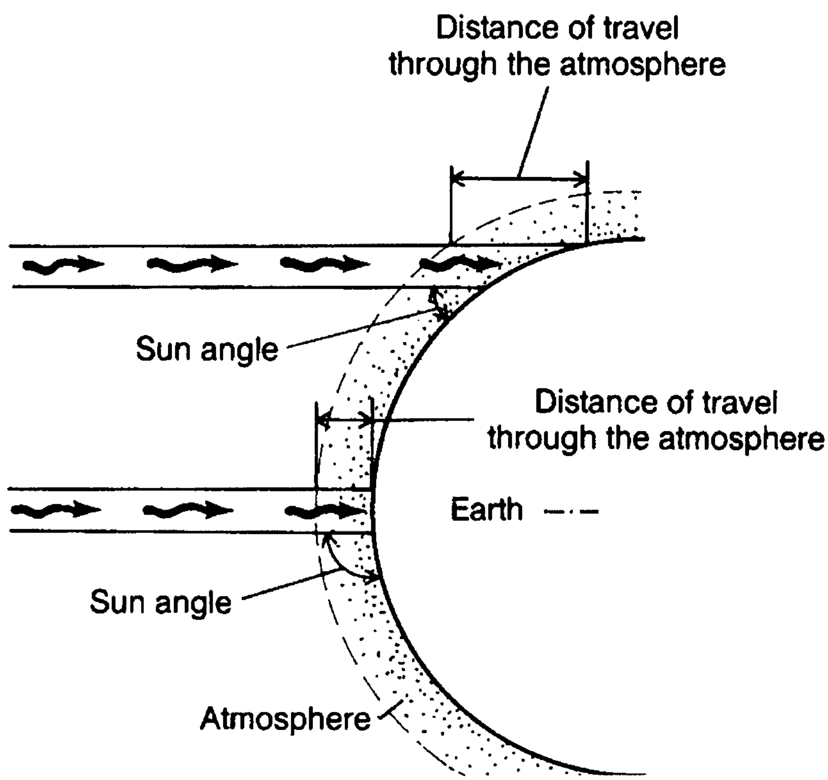
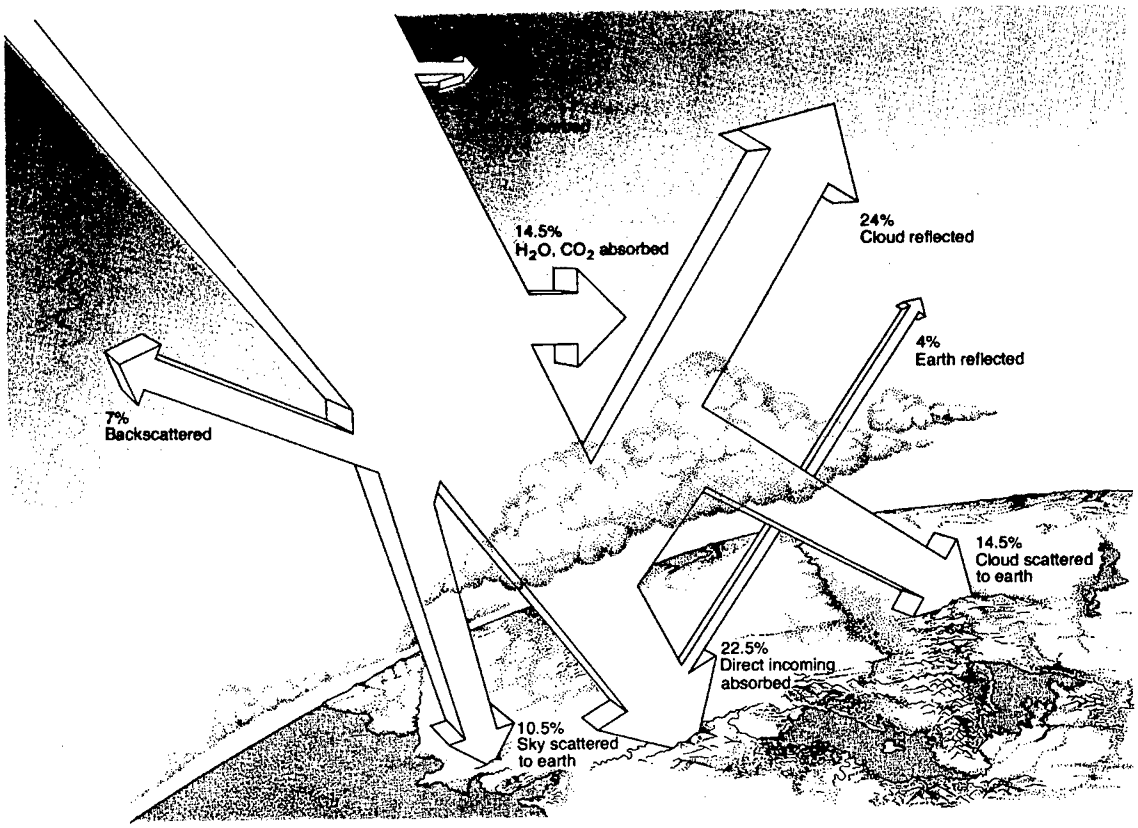


Figure 3-7. A high sun angle allows insolation to travel through less atmosphere than a low sun angle (Marsh, 1987). This lessons the amount of atmospheric interference and subsequent weakening of solar radiation as it moves toward the earth's surface. Therefore, all other factors being equal, areas that experience a high sun angle generally experience higher surface insolation rates.



Reflected by atmosphere and earth	Absorbed by atmosphere	Absorbed by earth
7% (backscattering)	3% (ozone)	10.5% (sky scattering)
24% (cloud reflection)	14.5% (CO_2, water vapor, water and dirt particles)	14.5% (cloud scattering)
4% (earth reflection)		22.5% (direct radiation)
35%	17.5%	47.5%
↓	↓	↓
Outgoing shortwave returned to space unchanged	*Heat* in atmospheric gases	*Heat* in land, water, vegetation
	Energy available to drive earth surface processes	

Figure 3-8. 65% of incoming solar radiation is available to drive earth surface processes. The atmosphere plays a great role in reducing the amount of insolation that strikes the earth's surface. In desert areas, the insolation reaching the surface is generally much greater than more humid regions (Marsh 1987).

negligible (Oke 1993). Temperatures in low latitude deserts vary from a mean of 29 to 35 degrees C (84 to 95 F) (Scott 1992). At Lugh Ferraui, Somalia, the average annual temperature is 31 C. The highest temperature officially recorded is 58 C (136 F) at El Azizia, Libya (Riordan and Bourget 1985). The highest yearly maximum temperatures (50 C or 122 F and higher) occur in deserts including the Sahara, Death Valley California, low-lying desert areas in Iran, and in western Pakistan (Riordan and Bourget 1985).

Compared to temperate regions, insolation and the radiation budget are also high in midlatitude deserts. The temperature regime in these deserts however, varies considerably between seasons. Midlatitude desert summers are warm to hot, with highs from 30 degrees to 40 degrees C (86-104 F). Nighttime lows, even in the summer, can cool 10-20 degrees C (18-36 F) from the daytime high (Scott 1992). The average winter temperatures vary with location, but both North America and Eurasia are within reach of winter arctic air masses and can experience temperatures as low as –40 degrees C (-40 F) in the American Great Plains, and –45 C (-56 F) in eastern Asia (Scott 1992).

The typically large diurnal and seasonal temperature ranges in deserts present dynamic conditions to which troops must adapt. Both diurnal and seasonal temperature ranges are greatest in midlatitude deserts, but low latitude deserts experience wide ranges as well. Rapid heating during the day and rapid cooling at night in deserts can be attributed to several causes. Clear skies and low atmospheric humidity common to these regions are largely responsible, allowing insolation to reach the earth's surface with little interference and limiting the greenhouse effect. Desert surfaces are generally excellent

absorbers and radiators of insolation. Heat transfer processes are rapid, in part, because of a lack of surface moisture and vegetation, and particularly because of the lack of ameliorating effects of evaporation. The specific heat of dry soil and rock is low, causing rapid absorption of insolation during the day, and encouraging rapid dissipation of energy back into the atmosphere at night (Oke 1993). Dry soil or rock are poor conductors of heat, and allow no mixing as common to fluids, so radiation energy is not well distributed to depth in surface materials, again encouraging rapid heat dissipation in the evening (Oke 1993). Average diurnal temperature range in low latitude deserts is 14 to 25 C (25 to 45 F), but can be much greater. For example, at In-Salah in the Sahara, the temperature dropped from an afternoon high of 52.2 C to –3.3 C (126 – 26 F) the following morning, a range of 55.6 C (100 F) (Heathcote 1983).

The Influence of Desert Temperature and Insolation on Troops: Operations in desert environments are fatiguing, both mentally and physically, primarily because of high insolation and temperatures. An abundance of insolation sunburns exposed skin, chaps lips, and damages mucous membranes. Even low levels can cause dazzle, or the temporary impairment of vision due to bright light. High temperatures are particularly debilitating. Mean annual temperature in desert areas, particularly low latitude deserts, is known to be high, yet the temperature of surface material is still greater. It is common for desert sand at the surface to exceed 73 C (165 degrees F). The human threshold of pain is 49 C (120 degrees F) and temperatures as low as 60 degrees C (140 degrees F) may cause first degree burns (Collins 1998). Temperature inside armored vehicles

operating in North Africa in World War II routinely exceeded 43 C (110 degrees Fahrenheit) (Toppe 1952).

Extreme desert heat has historically been a major cause of military casualties, even in modern times. During the 1967 War between Israel and Egypt for example, the Egyptians suffered over 20,000 heat casualties, and the Egyptians were acclimatized (Dreyfuss 1991; Fort Sill Safety Office 2002). More recently, in 1982 during the peacekeeping operation in the Sinai, one U.S. Army Company sustained 30 percent heat casualties (Fort Sill Safety Office 2002). When troops don Mission Oriented Protective Posture (MOPP) chemical protective suits (Figure 3-9) the potential for heat injury is significantly increased. High heat makes acclimatization necessary before troops from temperate regions can perform well and escape high rates of heat injuries. Acclimatization to the desert environment can be accomplished within two weeks with progressive exposure to heat and physical exertion (Departments of the Army Navy and Air Force 1980; United States Army Armor School 1993).

Characteristic high desert heat produces other effects challenging soldiers. High heat creates optical path bending that creates mirages, shimmering or 'heat waves' and makes objects appear in false locations. Shimmering of objects viewed through the lower atmosphere is caused by multiple refraction of light as it passes through a field of vertically arranged filaments of air at different densities (Oke 1993). The density differences result from extremely unstable air immediately above a hot surface. As radiant energy from the sun is absorbed by surface objects and rapidly re-radiated without

Figure 3-9. Mission Oriented Protective Posture (MOPP) suits include the protective mast, charcoal lined trousers and top, rubber gloves and rubber overboots. Shown here in a temperate environment, the added protective clothing creates significant challenges in hot weather.

the ameliorating effects of moisture evaporation, air within a meter or two of the surface becomes very hot relative to surrounding air and it rises rapidly and spontaneously, but not evenly (Oke 1993). This causes optical path bending and shimmering. In World War II in North Africa, visibility beyond one kilometer was at times 'practically impossible" because of these conditions (Toppe 1952, 83). Modern doctrine warns of mirages and difficulties with range estimation. Even laser range finders are susceptible to optical path bending from extreme surface heat and may provide inaccurate range returns over 1500 meters in desert regions (United States Army Armor School 1993).

The large diurnal temperature changes common to desert environments also create significant challenges for soldiers operating in the region. Ignorance or misperception of desert temperature regimes encourages troops to ignore the need for cold weather gear. However, even moderate nighttime temperatures seem cold after exceedingly hot days and the potential for cold weather injuries, particularly amongst the wounded, is high. The German Afrika Corps issued 'bellybands' of warm cloth for troops to wear at night to help retain proper core body temperatures (Toppe 1952). Packing lists for U.S. troops going into operations in desert environments habitually include cold weather and rain gear.

The Influence of Desert Temperatures and Insolation on Equipment: Hot desert temperatures are not only debilitating to troops, but also present challenges to military equipment. High atmospheric temperatures cause engines and transmissions to run 10 – 20 degrees F warmer than normal (Center for Army Lessons Learned 1990b) and overheat more readily. Electronic equipment is susceptible to thermal cutouts as electronic failsafe systems shut down radios, radars, chemical detectors and other imperative equipment (Center for Army Lessons Learned 1990b). Soldiers are trained to place wet cloths on radios to allow evaporation to help keep the equipment cool (Center for Army Lessons Learned 1990b). Excessive heat can cause ammunition to behave erratically, forcing troops to take special handling precautions that include double shade structures and burrowing storage areas a meter below the desert floor (Center for Army Lessons Learned 1990b).

High temperatures cause batteries to fail more quickly in deserts. It is common for batteries to die in vehicles that remain inactive in a desert environment for 5-10 days (Center for Army Lessons Learned 1990b). Given the dependence of modern armies on batteries to run modern electronics, this problem is not a small one. A single U.S. Armored Division requires 3,660 batteries to power systems on 327 Abrams tanks and 283 Bradley Fighting Vehicles. This number does not include batteries required for night vision goggles/sights, helicopters, generators, computers, chemical alarms or a host of other systems (Collins 1998).

The typically large diurnal temperature change in deserts greatly affect direct and indirect fire systems as well. Despite the protection of thermal shrouds designed to distribute heat to the barrel evenly, tanks and other weapon systems experience 'gun tube droop' as the temperature changes on a daily cycle. As the gun tube bends in response to differential heating, the ballistic solution changes significantly and must be corrected. Repetitive tank boresighting and muzzle reference changes are required throughout the day and night to insure accuracy (United States Army Armor School 1993).

High insolation in desert regions damages equipment and can mark positions through reflection of visible radiation off glass, metal, and dust and wind goggles. Insolation degrades rubber, plastic, lubricants, pressurized gasses and some chemicals as well as infrared tracking and guidance systems (Cutting 2002). The German Afrika Corps in World War II eventually replaced all leather with cloth (expect for footwear) because of insolation degradation (Toppe 1952). Direct sunlight in particular degrades

modern M13 chemical decontamination and reimpregnating kits and other sensitive equipment (Center for Army Lessons Learned 1990b).

The Influence of Desert Temperatures and Insolation on Tactics: Armies operating in the high temperature and high insolation desert regime must adapt TTPs to fit this environment. One effective adaptation is to limit hard physical exertion (if possible) during the highest insolation/temperature periods of the day. These periods do not conform to the period of highest insolation because there exists a time lag between the input of short wave solar energy and the generation of long-wave energy reradiating into the atmosphere from the surface (Figure 3-10). The highest insolation times are generally between 1100 and 1500 hours. The greatest atmospheric temperatures are between the hours of 1300 and 1700. In order to cope with the sensible heat, the German Army in North Africa during World War II observed a three hour 'quiet time' at noon (Toppe 1952). Likewise, during preparations for the Gulf War, U.S. troops followed similar restrictions (Dreyfuss 1991; Suchan 2002). Because of high insolation and temperatures during the day, night operations take on added importance in the desert. Modernized armies enjoy a distinct advantage at night because of electronic vision capabilities such as infrared and thermal sights.

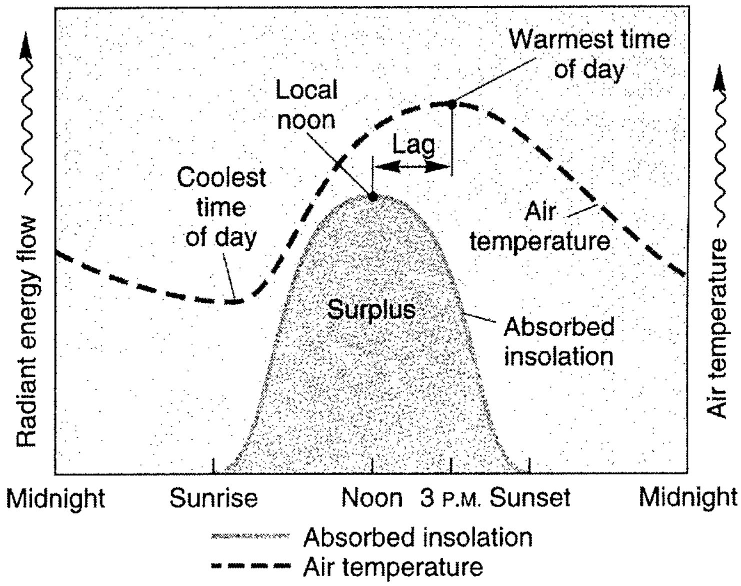


Figure 3-10. Typical daily radiation curves (Christopherson 1997). This graph shows the lag time between periods of highest insolation and air temperature.

Temperature and humidity have a direct impact on aircraft performance as well. Air density decreases with increasing temperatures and humidity, reducing the efficiency of aircraft propulsion and lift capabilities. Aircraft flying in hot desert temperatures must carry a decreased payload, and experience increased fuel expenditure and decreased range. FAARPs (Forward Arming And Refueling Points) may have to be positioned closer to potential strike points, air refueling for fixed wing aircraft takes on added importance, and runways have to be longer.

The effectiveness of Nuclear, Biological, and Chemical (NBC) and smoke operations is directly proportional to air stability (United States Army Armor School 1993). Desert air tends to be most stable at night and in the early morning hours because surfaces have cooled and are not producing significant long-wave re-radiation that causes

higher near-surface atmospheric temperatures and instability. Night and early morning hours are therefore the best times to deploy NBC or smoke agents in order to avoid irregular dispersion and possible danger to friendly units. Conversely, hot desert temperatures in late morning and the afternoon may act to reduce static overpressures from nuclear devices, somewhat mitigating their effectiveness (Collins 1998). Daytime hot, unstable air, high insolation, and arid conditions tend to dissipate nuclear fallout and non-persistent chemical agents quickly. High insolation and temperatures are also effective in rapidly killing many types of biological agents (United States Army Armor School 1993). Conversely, a credible threat of NBC operations in a region requires troops to repeatedly don MOPP gear, which substantially decreases their ability to perform in hot environments.

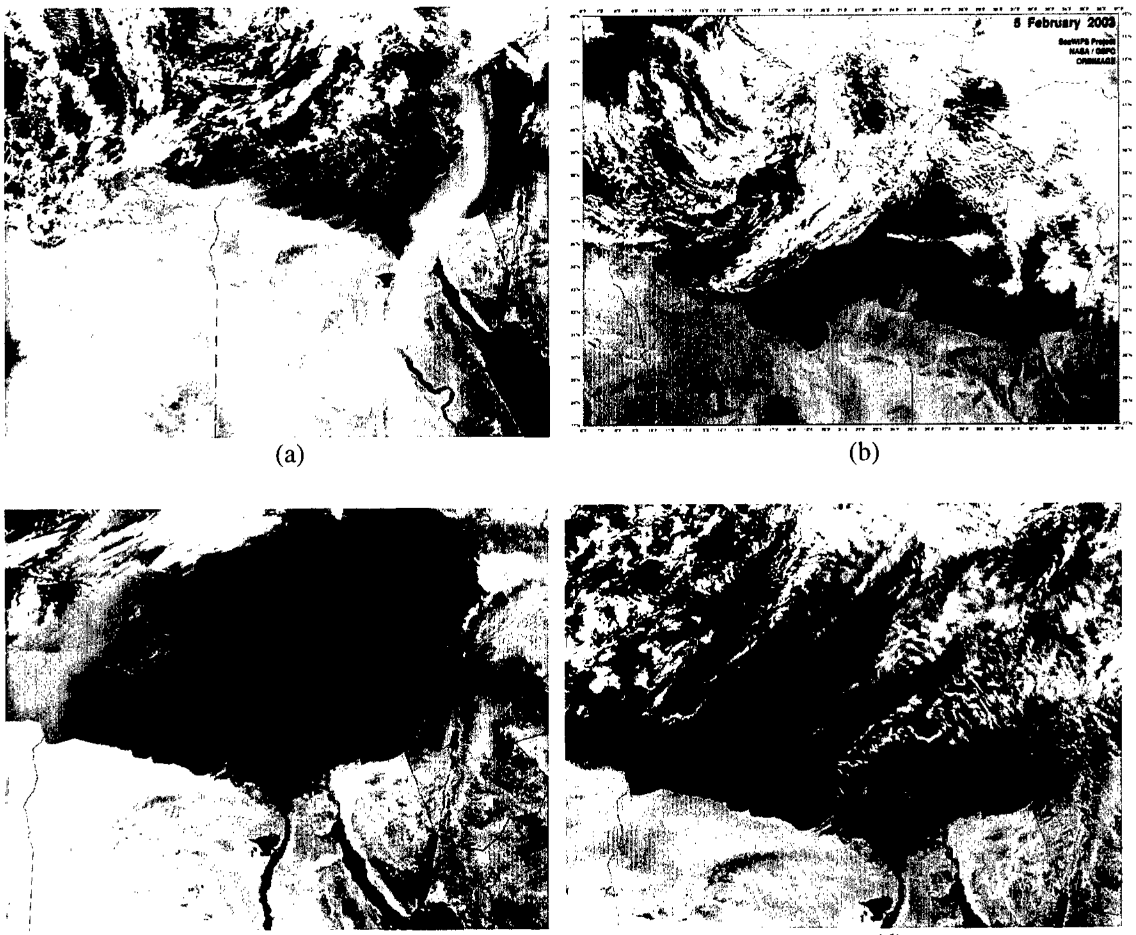
Aeolian Processes

Desert dust can be debilitating to troops, is brutal on equipment, and has important consequences to tactics. Dust consists of fine silt size or smaller particles (< .06 mm diameter) that are suspended in the atmosphere (Thomas and Goudie 2000). In desert regions, dust is dominated by silica, mainly in the form of quartz particles, but may also include other desert minerals such as feldspars, calcite, dolomites, cholorite, kaolinite, mica, illite, smectitie, palygoskite, heavy oxide and silicate minerals, gypsum, halite, opal and others, including organic materials (Middleton 1989).

The mode of aeolian transport is dependent primarily on the grain size of the available sediment (Bagnold 1941). Small particles (< 60-70 microns) are transported in

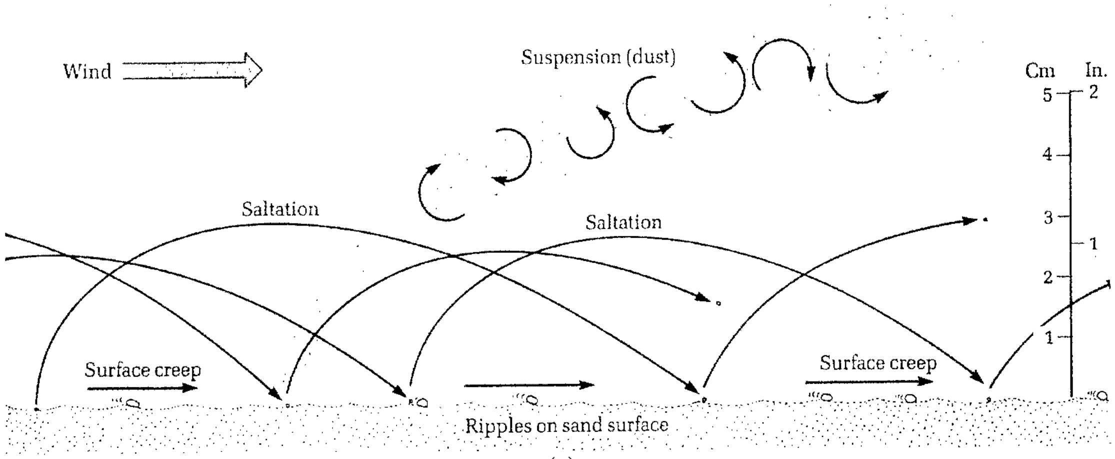
suspension where turbulent eddies in the atmosphere can keep fine sediment entrained for days, and airborne dust can be transported thousands of kilometers from source areas (Thomas and Goudie 2000) (Figure 3-11). Larger sediment particles (approximately .06 – 1 mm) move through saltation. Larger (> .5 mm) or less exposed particles move through traction (Lancaster and Nickling 1994) (Figure 3-12). 75% of the total transport rate of aeolian-moved material in dry lands is shifted by saltation (Bagnold 1941; Willetts and Rice 1986). Deflating dust causes abrasion by friction and the impact of sand grains is most effective just above the surface (Cooke et al. 1993) where soldiers and their equipment operate.

Winds that raise dust are caused by the dynamic interaction of atmospheric temperature, pressure and insolation. Global winds correlate to large pressure differentials associated with worldwide circulation patterns, but local winds result from physical characteristics in a specific area. Local desert winds are often violent and persistent, with velocities of 80-100 km/hr (50-60 mph) (Fairbridge 1968), stripping hundreds of millions of tons of dust each year (Cooke et al. 1993). Desert convectional winds are formed from pressure gradients developed by extreme differences in temperatures of the air layer immediately above ground level, due to differential heating of surface materials. As air heats, it expands and rises, creating a relatively low-pressure area in the hottest regions, and thus creating advective winds, which can be of great force locally. A small-scale local wind known as a 'dust devil' is common to desert areas, although it has little military importance. Related to intense local heating, winds of up to 55 kph can be generated within these short-lived disturbances (Cooke et al. 1993).

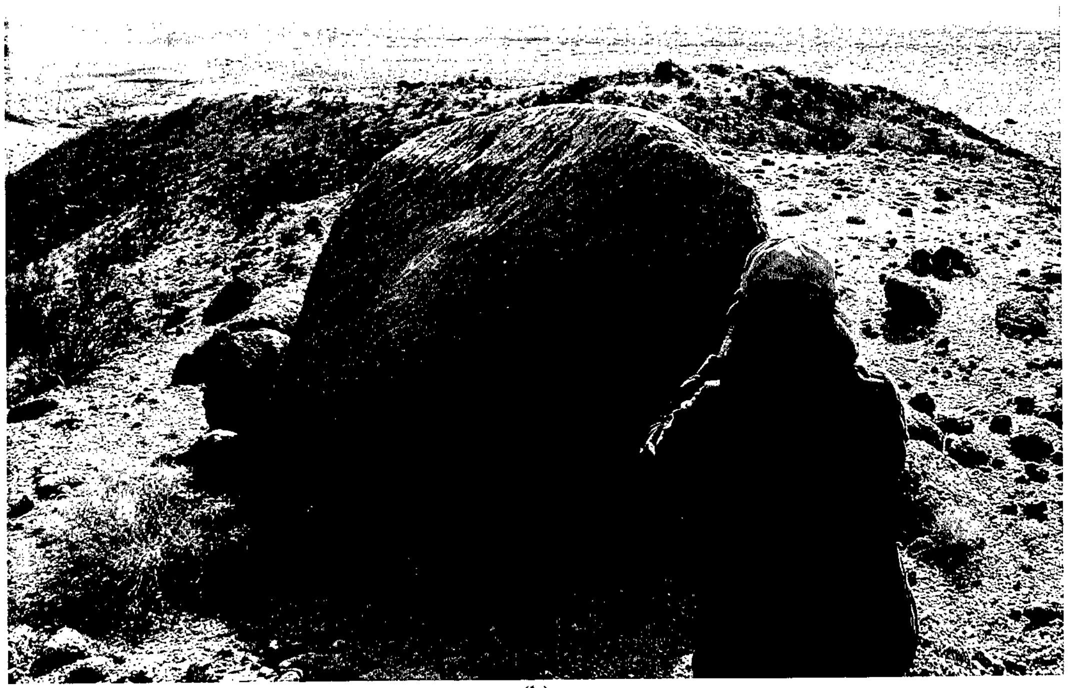


(a) (b) (c) (d)

Figure 3-11. Dust can move thousands of kilometers in suspension. These true color images of dust plumes moving from North Africa across the Mediterranean were taken by the Moderate Resolution Imaging Spectroradiometer (MODIS) aboard NASA's Aqua satellite in early 2003 (NASA 2003). (Country borders superimposed.)



(a)



(b)

Figure 3-12. Larger grains of sediment moved by the wind travel by saltation and traction, or surface creep. The smallest particles are carried in suspension (a). Abrasion by these particles can be significant and is concentrated within a meter of two of the surface. This rock (b), known as a ventifact, is scarred from the collision of countless sediment particles transported by persistent winds

Dust storms are common in most deserts (Goudie 1978; Middleton, Goudie et al. 1986), partly because of the great amount of small, loose particles laying on the surface, and partly because of common high velocity local winds. These storms can be brutal for troops operating in the area, cutting visibility to less than a meter and literally stopping all movement. Coalition troops operating in Operation Free Iraq, for example, were caught in huge dust storms on 24-25 March 2003, slowing their advance (Espo 2003). Goudie (1978) indicated that as many as ten dust storms occur in Egypt each year, as many as twenty occur per year in West Africa and thirty in China.

The susceptibility of desert surfaces to deflation varies with climate, soil conditions and vegetative parameters (Brazel, Nickling et al. 1986). While local conditions can be extraordinarily complex, it is possible to delineate areas most susceptible to dust storm activity on a small (worldwide) scale (Middleton et al. 1986) These locations include:

- Alluvial plains of the Tigris-Euphrates system
- Lake sediments of the Bodele Depression in the Sahara
- Alluvial plains of the Niger River and de-vegetated dunes of southern Mauritania
- Alluvial and loessic deposits of the Upper Indus plains
- Salars and associated fans of the Andean region
- Ancient cover-sands and fluvial sediments of the High Plains in the United States
- Closed basins and fans of the Seistan Basin
- Alluvial and lacustine deposits of the Aral-Caspian system
- The great loess belt of China
- Fans, dune fields and playas of the Tarim Basin
- Lake Eyre basin and its feeding plains

Hot, seasonal winds from the heart of desert regions are extremely desiccating and routinely bring dusty, uncomfortable and debilitating conditions. These winds raise temperatures and lower visibility, and are at times, strong enough to stop all movement. They may last for days at a time. In Egypt, they are called *Khamseen* ("fifty" in Arabic) for the number of days they can occur each season. They are known by other names depending on location, including *Harmattan*, in Southern Sahara, and *Ghibli*, in Libya.

While desert dust is naturally generated by the force of wind, direct human action can exacerbate dust production and produce militarily significant dust. Cattle grazing, mining, construction, agriculture, construction of flood control devices and human movement over desert terrain can greatly accelerate erosion and the capacity of local winds to carry dust (Wilshire 1980). Military maneuvers disturb vegetative cover and destroy or damage indurated surfaces, allowing accelerated deflation by the wind. The movement of soldiers and vehicles themselves generates voluminous dust in the right conditions. Each time the desert surface is disturbed, loose surface particles, particularly of clay and silt size are moved and entrained in the atmosphere as dust. Foot movement creates some dust, but the amount created by tracked vehicles or aircraft for instance, is considerably greater (Figure 3-13). Dust is a significant military consideration because it marks movement and firing locations and it obscures observation of enemy activity.

The Influence of Desert Winds and Dust on Troops: The most obvious influence desert dust has on humans is that it limits the excellent visibility commonly enjoyed in desert regions. This has far-reaching effects on tactics, but dust and desert

(a)

(b)

Figure 3-13. (a) A C-130 Hercules aircraft takes off from a field in the Mojave Desert, California (Envirotac II 2003). (b) A M1A1 tank crosses a fine particle surface in Kuwait (JCCC 2003).

winds can also be physically demanding on troops. Constant winds and dust dry out mucous membranes, causing chapped lips and nosebleeds. Irritative conjunctivitis, caused when fine dust particles enter the eyes, is a frequent problem in deserts (United States Army Armor School 1993). Constant wind noise is tiresome and can reduce personnel effectiveness, and sandstorms can effectively prevent military movement at times, such as recently experienced by coalition troops fighting in Iraq in March 2003 (Espo 2003).

Of particular concern to troops are the diseases that can be spread by desert dust. The Kalahari Desert of Botswana, Africa may have the highest worldwide death rate from lung disease because of dust inhalation (Pewe 1981). The southwestern United States is an endemic area for the human disease *coccidioidomycosis*, also known as "valley fever," a serious disease caused by the fungus *Coccidioides immitis*, which occurs in the soil of semiarid and arid areas and is disseminated by blowing dust. Desert soils may contain any number of fungi that can cause disease in humans (Table 3-11), any of which may increase casualty rates in these regions significantly.

Desert Winds and Dust and Equipment: Dust is particularly hard on military equipment, both mechanical and electrical. It penetrates into gearboxes, engines, weapons and electronics. Dust mixed with lubricants forms an abrasive paste that accelerates wear. Dust contaminates tools, fuel, and repair parts, and is difficult to keep out during field repairs. Table 3-12 details some of the major effects dust has on military equipment in the desert, although it is difficult to convey the complete impact.

Table 3-11. Medically important fungi isolated from soil surface dust near Phoenix, Arizona from 1913-1916, modified from Leathers (1981).

Species	Disease produced	Consequences
Aspergillus clavatus, Aspergillus flavus, Aspergillus niger	Aspergillosis	Causes infectious disease of the lungs, and may result in fever, chills, shock, skin lesions, and multiple organ failure.
Candida albicans	Candidiasis	Yeast infection affecting skin and mucous membranes.
Cladosporium carrionii	Chromomycosis	Causes skin lesions which can lead to ulceration.
Coccidioides immitis	Valley or Desert fever	Infectious disease that occurs in two forms. The primary form is acute, benign, self-limiting respiratory disease. The progressive form is a chronic, often fatal infection of the skin, lymph nodes, spleen, liver, bones, kidneys, meninges, and brain.
Geotrichum candidum	Geotrichosis	Candidiasis-like infection affecting bronchi, lungs, mouth or intestinal tract.
Microsporum canis, Microsporum gypseum	Ringworm	A superficial infection affecting skin, nails, or hair.
Nocardia asterioides, Nocardia brasiliensis	Nocardiosis, Mycetoma	Acute or chronic infectious disease affecting lungs. May cause skin or subcutaneous abscesses, lung lesions, pleural effusion, and metastatic brain abscesses.
Phialophora jeanselmei	Mycetoma	Infectious disease of the feet, causing lesions or abscesses. If untreated, will destroy muscles, tendons, and bone.
Phialophora verrucosa	Chromomycosis	Causes skin lesions which may lead to ulceration.
Sporothrix schenckii	Sporotrichosis	Infectious disease causing nodules, ulcers and abscesses. Usually confined to the skin and superficial lymph channels, occasionally affecting lung or other tissues.
Trichophyton ajelloi	Dermatophytosis	Infectious disease causing accumulation of excessive lymph fluid and swelling of subcutaneous tissue of the foot. May cause chills, high fever, red, hot, and swollen leg.
Trichophyton mentagrophytes	Athletes' foot (Tinea pedis)	Infections beginning in the space between the 3rd and 4th toe, may spread to the arch. Affects skin and nails.

Table 3-12. Generalized effects of desert dust on modern military equipment.

Equipment Category	Major effect
Weapons	• Pits optics. • Dust sticks to lubricants • Jams small arms • Missiles stick on launch rails • Gun barrels wear quickly or plug up, causing in-bore detonation
Vehicles	• Requires lube and oil changes twice as often • Quickly clogs air filters • Causes parts to fail 50% more quickly, placing additional strain on logistical system • Accumulation of dust at the bottom of engine compartments often becomes soaked with fuel and oil, creating a significant fire hazard
Fuel	• Static electricity in the atmosphere can cause explosions during fueling operations
Electronics	• Clogs heat sinks and ventilation ports • Static electricity in atmosphere degrades radio signals • Abrades insulation on wires and cables • Clogs electrical contacts

The Influence of Desert Winds and Dust on Tactics: Natural or anthropogenic movement of particles from strong winds can either constrain military operations or provide opportunity. Winds shifting unconsolidated sands often expose or bury minefields, for example, limiting their effectiveness. Shifting sands can close roads vital to logistical support or military maneuver. Huge dust storms limit visibility and can stop operations altogether as they did routinely in North Africa during World War II (Toppe 1952; Perrett 1988) and during Desert Shield in 1990-91 (United States Dept of Defense 1992; Suchan 2002). A sudden dust storm in April of 1980 caused disaster for U.S. military personnel attempting to rescue Americans held hostage by Iran. The storm cut visibility to near zero as the American rescue team was maneuvering out of a desert staging area, contributing to a collision between a C-130 Hercules fixed wing aircraft and

a RH-53 Sea Stallion helicopter. Crewmen aboard both aircraft were killed (Gilewitch 1993-1996).

Dust created by humans often has an even stronger influence on desert tactics than does naturally occurring dust. Any movement in the desert raises some dust, but the operation of modern tracked vehicles, wheeled vehicles and aircraft inevitably creates dust that marks positions and blinds vehicle crews (particularly helicopter crews). Rapid maneuver by ground vehicles in tactical formations becomes challenging. Landing a helicopter in most desert locations raises enough dust to be extremely dangerous because the ground and horizon are often invisible to the pilot as dust is blown into the surrounding air by "blade wash."

Dust can act to limit battle damage assessment once rounds are fired. The openness of desert terrain makes dust raised by movement or by firing weapons easily spotted. The Javelin manportable antitank system and the TOW (Tube Launched, Optically Tracked, Wire Guided) Antitank Missile for example, key weapons in the U.S. antitank inventory, are being developed with 'fire and forget' technology so soldiers may immediately take cover after firing, thus mitigating problems raised by their dust signature (Association of the United States Army 2002).

Dusty conditions can provide opportunities in desert warfare as well. Tactics in desert regions are often modified to take advantage of dusty conditions. Deception is key to successful maneuver. Common tactics that mitigate or use the creation of dust to tactical advantage include moving along multiple routes to lessen the dust signature and deny the enemy knowledge of the main attack, or the prodigious use of feints. General

Rommel of the Afrika Corps placed airplane propellers and engines on vehicles to raise huge volumes of dust and give the impression of large vehicle movements (Toppe 1952). Night movement is particularly valuable to conceal the generation of dust by movement, especially when the forces involved are modernized with night vision equipment that provide a tactical edge over less modern forces.

Successful movements of large modern forces in the desert often use dust signatures and the great visibility common to the region in deception operations. The penultimate example of successful deception in desert warfare may be Egypt's preparations for the 1973 Ramadan (Yom Kippur) War with Israel. The Egyptian armed forces mounted a surprise attack on the Bar Lev defensive line across the Suez Canal in the Sinai Peninsula. Israelis enjoyed the clear visibility that desert terrain provides across the western bank of the Suez Canal and could observe military preparations. Egyptian forces created an atmosphere of normality by routinely conducting strong feints toward the canal they would eventually cross. In each of 22 sudden and massive movements, Egyptian forces dashed to the front, raising large columns of dust easily seen by the defenders (Watson 1995). The actual attack was conducted on the coincidence of holy days in both the Islamic and Jewish calendars, that of the beginning of Ramadan, and of Yom Kippur (Herzog 1984; Aker 1985). Surprise was nearly complete.

Desert Terrain

Terrain refers to surface features, or topography, of a region. In general, desert terrain provides a relatively unencumbered surface for rapid movement and long-range

observation and direct fires, attributes that make desert warfare unique and greatly influence tactical choices. A unit's area of operation, interest, and influence are, on average, far greater in the desert than other environments. Maneuver warfare is therefore of paramount importance, yet desert topography is diverse and some desert areas are constrictive, providing opportunities for defense. At times, desert warfare can be a struggle for maneuver chokepoints such as road crossings, mountain passes, and water sources.

U.S. Army and Marine Corps doctrine, as provided by FM 90-3 (Desert Operations) (United States Army Armor School 1993), classifies three general types of desert topography – "Mountain," "Rocky Plateau," and "Sandy or Dune." "Mountain" deserts are composed of scattered ranges or hills characterized by an abundance of rock outcrops and the absence of round smooth slopes associated with mountains of more humid regions. Flat, wide, alluvium-filled basins separate isolated prominences and major ranges. Change in slope is abrupt rather than gradual as in more moist areas. Much of the infrequent rains fall on high ground and run off quickly in the form of flash floods, eroding deep wadis and depositing sediment in alluvial fans. Water evaporates rapidly, leaving the area as barren as before, although ephemeral vegetation may subsist. If the rate of rainfall exceeds the evapotranspiration rate, lakes high in salt content may form in low lying areas such as the Great Salt Lake in Utah or the Dead Sea. Military trafficability in this terrain ranges from good in some areas to poor in most.

"Rocky Plateau" deserts are large flat areas with exposed bedrock or desert pavement. Plains can be extensive, comprising as much as ½ to ¾ of the surface area.

The surface is diverse as well, and can be dominated by hammada (a region of boulders and exposed bedrock), or reg (an area of desert pavement), or any combination. Examples of rocky plateau deserts include the United States Army National Training Center in the eastern Mojave Desert in California, or the Golan Heights in Israel. Military trafficability in these areas is good to fair.

"Sandy or Dune" deserts are large areas covered with loose sand, generally arranged in some sort of dune formation by the wind. Some dunes may be over 1,000 feet high and 10-15 miles long, and trafficability is often restricted. Plant life is limited and observation and fields of fire may be over 3,000 meters. Examples include the Saharan ergs, the Empty Quarter of the Arabian Desert, and the Kalahari in South Africa. Military trafficability in these regions is poor.

These generalized terrain descriptions provide a starting point for understanding desert terrain, but a more detailed geographic appraisal can provide additional information to better characterize the complex environment. Table 3-13 provides such an appraisal of the variety and relative surface coverage of terrain types common to desert areas. General military trafficability is indicated. The table shows a great deal of open terrain that allows rapid maneuver not common to temperate regions, as many people perceive the desert to be. However, the table also demonstrates the reality that a large proportion of deserts are mountainous, with dissected terrain and difficult trafficability.

Table 3-13. Desert Terrain by area. Information modified from Heathcote (1983).

Landform Type	Arid Areas (Areas as % of total) SW USA	Saharan Desert	Libyan Desert	Arabian Desert	Australian Desert
A. *Playa:* flat, sun-baked expanse of clay and salt, periodic water cover; zero vegetation. Alternate names: salina, claypan, takyr Military Trafficability: Good when dry	1.1	1	1	1	1 (Playa)
B. *Desert flat:* relatively flat; relief 0.3-1.6 m, may include dunes up to 5 m high; slope 1 in 352; crossed by wadis; vegetation sparse. Military Trafficability: Good.	20.5	10	18	16	18 (Stony Desert)
C. *Bedrock fields*	0.7	10	6	1	14 (Shield Desert)
(i) *Pediment:* slightly inclined rock surfaces thinly veneered with fluvial gravels; slope 2°- 7°; surface coarse sand to boulders; vegetation common in wadis Military Trafficability: Good to poor					
(ii) *Desert dome:* convex surfaces with uniform and smooth slopes; 4-10 km diameter; 180- 700 m height; slopes 1°-4°; most vegetation types exist here. Military Trafficability: Good					
(iii) *Hamada:* bare rock of low relief; vegetation zero or sparse Military Trafficability: Fair to Poor					
D. *Regions bordering through-flowing rivers = canyonlands:* area eroded by tributaries to main stream ; terraced surfaces; includes some badlands; vegetation heavy Military Trafficability: Good to poor	1.2	1	3	1	?
E. *Alluvial fans and bajadas:* relative relief to 1 m - if dissected, to 18 m; constant slopes; detritus grades from gravel and boulders at apex to sand and silt at foot of slope; mud flows occur; vegetation sparse Military Trafficability: Generally good	31.4	1	1	4	13 (Clay plains and floodplains)

Table 3-13 (continued).

Landform Type	Arid Areas (Areas as % of total) SW USA	Saharan Desert	Libyan Desert	Arabian Desert	Australian Desert
F. *Dunes:* hills of windblown material (clay or sand); asymmetrical section with steep slip-off slopes to 32°; windward slopes 15°-19°. Sand movement bulk within 2 m of surface, 90% within 0.3 m of surface. Dune types reflect geometry of wind directions. Military Trafficability: Poor	0.6	28	22	26	38 (Sand Desert)
G. *Dry Washes:* dry wadis; U-shaped cross section; slope 2°-3°; sand, gravel & boulder bed; vegetation good Military Trafficability: Poor cross compartment, good traveling with the wadi at lower elevations	3.6	1	1	1	?
H. *Badlands:* rough dissected soft sedimentary rocks; relative relief to 30 m; clay, silt surfaces; vegetation sparse Military Trafficability: Poor	2.6	2	8	1	?
I. *Volcanic cones and fields:* recent volcanic surfaces; loose boulders, lava; slopes to 30°; vegetation zero Military Trafficability: Poor	0.2	3	1	2	?
J. *Desert mountains:* bare rock masses; granitic (rounded); metamorphic (angular); sedimentary (canyons, amphitheatres) Military Trafficability: Poor	38.1	43	39	47	16 (Mountains)

Regardless of the scheme used to depict the landscape, desert terrain can be accurately described as more vast, open and harsh than temperate environments. Deserts seem vast and open because they typically provide long-range visibility and their physical landscape is normally barren. Long range visibility exists because open plains and wide valleys are common, the atmosphere is usually clear of moisture, and vegetation is typically widely scattered or absent with much bare ground interspersed. Vegetation that

is present consists largely of scattered shrubs with either tiny leaves or no leaves at all to block the view. Dominant colors are browns, tans, grays, and buffs. Limited human development complements the monotonous landscape with a dearth of cities, roads, and agriculture to break up the terrain.

The Influence of Desert Terrain on Troops: Soldiers are trained to quickly adapt to a variety of terrain conditions. If time is available for training in similar regions, and for acclimatization, they do so with few problems. Jungles, for example, provide extremely limited visibility and soldiers adapt their skills to cope with this tight, dark, moist and congested environment. Conversely, desert terrain is characteristically vast and open, and soldiers must adapt to these conditions as well. On the modern battlefield however, troops understand that what can be seen, can be killed. Thus, when untrained personnel arrive in a desert theater, some soldiers may initially experience agoraphobia (fear of open spaces) because of the lack of natural concealment that is important to their survival (United States Army Armor School 1993). This condition usually passes with acclimatization and training.

The open, vast physical landscape of some desert regions challenges individuals in other ways. One key problem is difficulty in navigation and pinpointing locations. The flat plains of Southwest Asia for example, provided few observable terrain features to aid coalition solders orienteering during the Persian Gulf War. Without reference points visible on the ground, it is virtually impossible to orient a map for navigation or fire support. This shortcoming was overcome by extensive use of technology, especially

the Global Positioning System (GPS) network of satellites and hand held receivers (United States Dept of Defense 1992).

Desert Terrain and Equipment: Light forces such as dismounted infantry, are of paramount importance in successful desert combat operations, but these forces suffer from a lack of mobility that has acute repercussions in the rapidly trafficable and characteristically large expanses of desert terrain. Vast areas of operations typical of many potential desert theaters make the use of mobile forces, particularly in the role of a reserve, of critical importance. As illustrated in Table 3-13, harsh desert terrain provides a continuum between high trafficability areas such as dry playas to locations such as lava flows or dune fields that make movement extremely slow and difficult. Tracked vehicles retain a significant mobility advantage over wheeled vehicles in cross-country movement, and tank and mechanized infantry forces are preferred in the desert. Tank heavy tactical reserves often provide the mobility and long range firepower required.

Traversing desert terrain is hard on equipment, both personal and vehicular. Sandy surfaces and rough, angular, rocky surfaces are both difficult to negotiate for ground troops and require competing solutions. Desert combat boots designed for the Saudi Arabian desert during Desert Shield, for example, do not stand up to the rocky desert terrain found in Afghanistan (Cox and Cavallaro 2002). All-terrain wheeled vehicles that make up the Combat Service Support (CSS) fleets find trafficability difficult on the poor or nonexistent roads that commonly exist in an area of operations in desert regions. The 1st Brigade of the Saudi Arabian National Guard for example, suffered 161

flat tires moving from Riyadh to blocking positions during Operation Desert Shield in August 1990 (Collins 1998). Tracks, while better equipped to traverse rough terrain, are inappropriate for logistical tasks. When used in deserts, tracked vehicles suffer from increased maintenance requirements from strong vibrations when going over rocky terrain to heavy wear on engines and transmissions as they struggle to move their heavy weight through deep sand. General George S. Patton Jr. noted that vehicles during the World War II era should be expected to get only one-third of the rated mileage for fuel in a desert environment (Patton 1942).

Larger operating areas typical of desert theaters strain logistical systems simply because the distances involved are so great. Large areas in deserts must be traversed on unimproved roads or even cross-country because of the lack of infrastructure. Deserts rarely provide adequate material for forging needed supplies such as Class II & IV (Construction and Barrier Material) and water, both of which are particularly burdensome to haul. 4x4 timbers, plywood, pickets, and barbed wire for force protection must be draped across combat vehicles to transport it to where it is required because it cannot be obtained locally. Everything needed to wage desert warfare must be carried (Watson 1995).

The Influence of Desert Terrain on Tactics: Desert operations involve no changes in the fundamental tactical principles laid down by doctrine (Patton 1942), yet, as in all environments, adaptations must be made to fit the physical characteristics of landscape in order to be successful. Perhaps the most important aspects of desert terrain

that require significant tactical adaptations are the large areas of operations that result from openness of the terrain and the capability of rapid movement, and the harshness of the physical landscape.

An aspect of open terrain that quickly becomes apparent to troops in the desert is the significant increase in weapons engagement ranges. Visibility up to 30 km is common in some desert regions (Center for Army Lessons Learned 1990b), primarily because of the lack of leafy vegetation and low atmospheric moisture, promoting the effectiveness of long-range indirect and direct fires. In the 1973 Ramadan (or Yom Kippur) War between Israel and the allied nations of Syria and Egypt, Israeli tanks in the relatively closed mountainous terrain of the Golan Heights (and without the use of laser range finders) routinely engaged and destroyed Syrian tanks at the extreme range of 2,000 meters (O'Ballance 1978). M1A1 tanks in Desert Storm in 1991 consistently engaged enemy vehicles at well over their nominal doctrinal range of 2,500 meters (United States Dept of Defense 1992), at times firing and killing targets at ranges approaching 4,000 meters (GolbalSecurity.org 2002). The increased capability to destroy enemy targets at longer ranges increases a unit's area of control and influence, thus increasing the entire area of operations in deserts well beyond those experienced in temperate regions.

The military adage popular at the U.S. Army Armor School in the 1980s was "What can be seen, can be hit. What can be hit, can be killed." These words are especially important in modern desert warfare. High visibility and resultant long-range fires makes it imperative that soldiers disperse, camouflage, and dig in at every

opportunity. Congregations of men, material or vehicles are high payoff targets. Doctrinal distances common in temperate environments often need to be doubled in the desert, increasing difficulty for communications within units, making face-to-face meetings especially onerous and less common. Despite the lack of indigenous camouflage material, troops and vehicles should be camouflaged at every opportunity to at least deny the enemy knowledge of the type and number of potential targets. Soldiers and their vehicles should always be dug in to provide cover and concealment. This desert requirement necessitates an added logistical burden.

Further complicating defensive measures in the desert is the prevalence of a calcrete soil horizon in desert soils. Calcrete is commonly formed in desert environments experiencing 300-400 mm of precipitation per annum (Thomas 1989; Cooke et al. 1993), including North Africa and the Middle East. This hardened layer of mainly calcium carbonate forms centimeters to several meters beneath the surface and may be as thick as 2 meters or more. Soldiers digging individual fighting positions with only individual entrenchment tools are often not able to dig to an appropriate depth for protection in these areas. It is difficult to dig through calcrete even with modern field engineering equipment such as the SEE (Small Emplacement Excavator), or the M9ACE (Armored Combat Earthmover), thus greatly inhibiting the capability for units to build defensive fortifications for vehicles or soldiers.

Where terrain is open, as in the deserts of Western Iraq, North Africa, the Northern Sinai, portions of Southern Afghanistan and parts of eastern Iran, it becomes difficult to establish defensive positions simply because of the lack of significant terrain

features. Whereas a slight increase in elevation from broad tectonic warping for example, may provide suitable elevation for observation and adequate fields of fire, the lack of significant adjacent or complementary terrain features defies the defender's ability to anchor his flanks so the position cannot be turned. Iraqi forces, for example, attempted to anchor the right flank of their forward defensive positions facing coalition forces in Kuwait during the Persian Gulf War on the open, featureless desert of the Al-Muthanna Province. They believed their flank to be protected because they understood the region to be impassable. Their flank was turned. In WWII in North Africa, most defensive positions were small strong points centered on an elevated piece of landscape and linked by minefields. The famous 'left hook' strategy adapted by the Allies was a maneuver repeatedly and successfully used to maneuver around the open flank of the eastward facing Axis forces in North Africa, particularly during General Sir Archibald Wavell's 1940 - 41 offensive and General Sir Claude Auchinleck's offensive in 1941 (see Buell, Franks et al. 1978; Krasnoborski 1981).

In order to mitigate the effectiveness of maneuver on open desert terrain, units on the tactical or strategic defensive have often used mines as a substitute for terrain features. Minefields can be designed to deny flanks (protective minefields), to channel or turn the enemy's advance (tactical minefields), or to confuse the attacker (phony minefields) (United States Army Armor School 1995). Mines have been used extensively in desert conflict. Egypt, which has been the host of at least four wars since the beginning of World War II, claims over 17.2 million mines remain in the Western Desert (in northern Egypt bordering Libya) and 5.5 million in the Eastern Desert (mainly

the Sinai Peninsula) (Waguih 1999). There are over 50 minefields near El Alamein alone, 34 of which have not been mapped (Ministry of Defense 1991). Afghanistan, a desert region in constant warfare for decades, is also host for millions of leftover mines (Department of Geography & Environmental Engineering 2001a).

Regardless of the well-known advantages that open desert terrain provides modern (mechanized) forces, it is a mistake to think that all desert terrain is open. Table 3-13 clearly illustrates that not all or even most desert areas are flat and open, as many people perceive them to be. The North African Campaign during World War II, for example, was constrained by topography to the coastal region by the Saharan Ergs and the Qattara Depression (Toppe 1952). The Golan Heights of Syria and Israel are mountainous, rocky, and compartmentalized, but have been fought over many times (Herzog 1984). 70% of Afghanistan's terrain that was fought over from 1979-1989 by the Soviets and Afghanis, and more recently by U.S. and Coalition Forces, is mountainous (Department of Geography & Environmental Engineering 2001a) and unsuitable for armored maneuver warfare. Historically, desert strategic choke points are repeatedly the locations of battle. Mitla Pass in the Gebel al Raha Mountains of western Sinai, for example, has been fought for repeatedly because it lies on the best route through the peninsula directly to the Suez Canal crossing at the city of Suez.

Desert terrain is unique, with qualities that greatly affect tactics. While fundamental doctrine should not be changed, adaptations in TTPs must be made for operations to be successful within the changing processes and conditions that make up the desert region. Increased engagement ranges, larger areas of operation, and few

significant terrain features are just a few of the challenges that soldiers must overcome to successfully operate in the desert.

Discussion

The purpose of this study is to develop and assess a heuristic conceptual model that provides an alternative, complementary method to doctrinal, historical and topical studies in evaluating necessary adaptations to military operations in non-temperate operating environments. The model is designed as a technique to emphasize fundamental geomorphic processes and conditions that force military operational adaptations and that are not often emphasized in literature. It is responsive to the needs of the researcher, providing flexibility in the choice of geophysical topics that can be gleaned from literature synthesis to form the foundation of the analysis. The critical factor that this model provides is an approach that emphasizes the linkage between physical geography and military operations. It allows the researcher to systematically evaluate the effects of identified geomorphic processes and conditions on military troops, equipment and tactics, and provides insight that is not normally a critical consideration in other methods.

The application of this model to desert environments demonstrates each of these attributes. The rich database of literature that is available on desert warfare is impossible to synthesize because of its size and depth, yet the flexibility inherent in the model allowed selection of a suitable variety of works based on the researcher's interests and goals. This process resulted in the formation of an appropriate database for study that could be expanded upon as the need arose, or time allowed. The data uncovered in this

process also consisted of an enormous amount of information concerning the challenges soldiers face in the desert operating environment. This data had to be organized into categories for meaningful analysis. Fundamental geomorphic processes and conditions that directly link to military adaptations provided the necessary associations to support further investigation, and served to establish the critical relationship that this approach advocates – the linkage between physical geography and military operations. Finally, the investigation of how these geomorphic variables affect troops, equipment and tactics provides meaningful insight to soldiers and others as they relate these effects to their foundational causes.

The model presented in this chapter is designed for use with unfamiliar operating environments, and it can be widely adapted to provide a framework for investigating any number of regions where physical environmental interrelationships and dynamic processes may not be well understood. Despite this flexibility, the model is not suitable for all unfamiliar operating environments. It is inappropriate, for example, to apply the model to urban terrain. While urban areas can be considered an unfamiliar operating environment, cities can and do exist in all physical environmental realms. While the model may have some utility investigating warfare in specific urban environments, it is not designed to do so. The critical aspect this model emphasizes is the linkage between geophysical factors that differentiate physical operating environments with respect to military operations, an aspect that is not consistent in urban environments.

An understanding and appreciation of the physical realities of the desert operating environment as provided by this model may assist in lessening misconceptions and

provide a deeper understanding of the complex and dynamic regions that soldiers may face. Niccolo Machiavelli (as cited in Collins 1998, 27) postulated:

> In peace, soldiers must learn the nature of the land, how steep the mountains are, how the valleys debouch, where the plains lie, and understand the nature of rivers and swamps – then by means of the knowledge and experience gained in one locality, one can easily understand any other.

The conceptual framework presented here provides such a method to do this.

The model is applied here to the desert environment, but it can be successfully applied to arctic (tundra), jungle (rainforest) and mountain or other harsh environments that differ based on their physical characteristics and dynamic processes. The major importance of the model is not the content demonstrated in this chapter; rather the synthesis of geographic data into a military analysis of a region is the most important idea. None of the data presented here are new, but the approach used that is derived from dynamic geographical processes and conditions, provides a unique insight that is not well realized in the majority of publications considering non-temperate ground warfare. Its purpose is to enrich our thought process concerning potential conflict in non-temperate regions.

Conclusion

Operations in non-temperate environments will always challenge those soldiers who are familiar with and trained in temperate regions. It is important that troops expected to fight in unfamiliar conditions understand and prepare for the physical

environments they will encounter. Much of U.S. ground forces doctrinal (applied) publications concerning non-temperate environments deal with identification of environmental extremes and how to cope with them. Few publications step beyond this task-oriented approach and consider why, when, where and how these conditions exist. These considerations are important to understand if military leaders are to properly train their soldiers and marines how to fight in the region.

Despite the military's best efforts to train troops in harsh, unfamiliar regions, contemporary geopolitical realities dictate that the majority of U.S. forces be stationed in temperate areas. When crises arise in other environments, often units with little or no recent experience in these areas must be sent. The 1st Armored Division (AD), for example, was originally expected to participate in Operation Iraqi Freedom in early 2003 (Cox 2003). The majority of these units are based in the temperate environment of southern Germany, yet were prepared to deploy to the Persian Gulf region for possible action against Iraq where they would probably face desert combat operations at the height of the summer heat. Although 1st AD did not deploy, the 3rd Infantry Division (ID) stationed in the humid subtropical climate of Fort Stewart, Georgia, did deploy and is currently fighting in Iraq at the time of this writing. Other units, including the 7th Cavalry out of Fort Hood, Texas, also humid subtropical climate, and the 1st Marine Expeditionary Force out of Camp Pendelton, California, a Steppe climate, are also fighting in Iraq.

The future is certain to hold additional armed conflict in arid regions of the world. The better soldiers, politicians and other decision makers understand the influence of

fundamental physical geography on desert and other non-temperate environments, the better prepared they will be to cope with the military challenges these regions present.

CHAPTER IV: THE EFFECT OF MILITARY OPERATIONS ON DESERT PAVEMENT: CASE STUDY FROM BUTLER PASS, ARIZONA

Introduction

Environmental protection has failed to significantly influence military war planning or execution. As a result, damage to the physical landscape occurs with regularity during conflict and to a considerably lesser extent during training. Indeed, governments at war often order deliberate destruction of the environment, causing considerable change to morphology of the physical landscape (Table 4-1). The purpose of this research is to analyze alteration of desert surfaces caused by military operations. Specifically, this study investigates the effects of decades-old tank maneuvers across desert pavement in the Butler Pass area of southwestern Arizona.

Military tracked vehicle maneuvers in the southwestern United States in the early 1940s left scars of known origin and time. This event provides an opportunity to examine desert pavement modification and natural regenerative processes that have taken place at this site. Results of this study may be useful in establishing military training protocols pertaining to the management of public lands, particularly in the arid southwestern United States where both military and civilian land managers struggle to deal with the impacts of increased use of the desert. This research also contributes information to the debate among geomorphologists regarding the formative and regenerative processes that result in desert pavement. While some scholars attribute the

Table 4-1. Selected examples of deliberate physical landscape destruction by governments at war.

Military Action	Effects and Comments	Selected Examples
Employment of scorched earth policy	Crop and irrigation damage changes erosion and deposition patterns.	• Persian-Scythian War, 512 BC – the Scythians slowed the Persian advance by burning their own crops and buildings in the route of the invasion. • Napoleonic Invasion of Russia, 1812 – the Russians overextended French logistical support by denying them the ability to use and stockpile local supplies before the winter. • American Civil War, 1864 – U.S. troops under General Sherman marched from Atlanta to the Atlantic coast, burning or otherwise destroying all crops, stores, and animals within a 60-mile wide swath to break the will of the Confederacy to continue the war.
Causing deliberate flooding	Alters stream channels, deposition and erosion regimes. Dam busting deliberately destroys downstream anthropogenic and natural resources, forming new channel morphometry, river terraces, cut banks, etc.	• Franco-Dutch War of 1672-1678 – the Dutch slowed the French invasion and saved Amsterdam by destroying dikes and levees, flooding the lowlands along the axis of advance. • During World War II, the Allies destroyed two dams on the Ruhr River to destroy German factories in the Ruhr River floodplain.
Use of artillery, bombs, and mines	Rearrangement of the landscape resulting in craters, alteration of the upper soil profile, and destruction of vegetation with subsequent changes to erosion and deposition patterns.	• World War I, 1916 - The landscape of Verdun, France is pockmarked today after millions of tons of artillery shells were fired during the 10 month Battle of Verdun between France and Germany. • Vietnam Conflict, 1965 – 1972 - Over 20 million craters cover over 1/3 of Vietnam from United States bombing and artillery.
Use of chemical agents	Herbicides destroy vegetation and damage soils, thus altering erosion and deposition patterns.	• Vietnam Conflict, 1965 – 1972 – The United States sprayed over 18.2 million gallons of Agent Orange, Blue and White (defoliants) on the tropical rainforest and croplands of Vietnam.

Table 4-1. Continued

Destruction of Oil fields	Causes persistent formation of 'Tarcrete' oil sediment sludge and oil lakes.	• Persian Gulf War, 1991 - Retreating Iraqi forces set fire to over 730 Kuwaiti oil wells.
Use of nuclear weapons	Creates large craters, widespread destruction of all life including vegetation with subsequent changes to erosion and deposition patterns.	• World War II, 1945 - The United States bombed the Japanese cities of Nagasaki and Hiroshima to bring an end to the war.
Maneuver with wheeled and tracked vehicles	Virtually all cross country vehicle movement compacts the soil, decreases infiltration, destroys vegetation, and alters erosion and deposition patterns.	• All modern conflicts.

formation of pavement primarily to deflation (Walther 1891; Leet, Judson *et al.* 1978), others believe upward migration of pebbles (Springer 1958; Yaalon 1959-1994; Jessup 1960; Cooke 1970), overland flow (Sharon 1962), gravel shattering (Amit, Gerson *et al.* 1993) or the accumulation of fine sediment beneath the surface (Mabbutt 1977; Jessup and Coakley 1982; McFadden 2001) are more responsible.

By comparing track scars to adjacent control surfaces of undisturbed pavement, I discern the type and relative strength of regenerative processes at work in the study site since the creation of the alteration. The chapter organization starts with background information that places this research in the broader framework of military geography and provides an overview of the desert pavement literature, focusing on differing theories of surface particle formation. I then review previous research considering vehicular effects on desert landscapes. An introduction to the study area follows, then a detailed dialogue on track scar selection and methods used to evaluate differences between areas scarred by

tracks and undisturbed surfaces. The last sections present results of analyses, discussion and conclusions.

Military Geomorphology

Military activities cause permanent and prominent physical alteration of landscape in both cultural and physical realms that can provide geomorphologists unique opportunities to better understand natural processes, particularly at long time scales. Some of the earliest expressions of military operations remain key components of contemporary landscape morphology such as ancient road networks established to provide rapid military movement to quell rebellion or react to foreign invasion. The most famous of these include the extensive transport network of the Romans in Europe and around the Mediterranean (Adams and Laurence 2001) and the Inca in South America (Hyslop 1984). Walled cities and castles built to protect occupants from invading armies are preserved in the cultural landscape throughout the world. Other ancient military-altered landscapes include fortifications such as castles and other defensive works such as Hadrian's Wall and the Great Wall of China (Macksey 1974; Fryer 1977; O'Sullivan and Miller 1983).

Recent and spectacular military alterations to physical landscapes exist where the conduct of battle changed huge portions of natural land morphology, providing geomorphologists with small-scale (large area) laboratories for study. The area around Verdun, France for example, still clearly displays pockmarked terrain resembling craters, gilgai, drumlins and hummocks from alteration by millions of tons of artillery rounds that

turbated clay-rich soil and regolith during World War I (Macksey 1974; Mason 2000). German fortifications along the Normandy coast in France remain well defined by surface mounds marking defensive positions that Allied troops stormed on 6 June 1944 as they invaded Europe during World War II (Allen 2002). More recently, vast regions of the Kuwaiti desert were artificially transformed into a faux duricrust landscape of sludge sediment and oil lakes (termed 'tarcrete') created by the destruction and burning of over 730 oil wells during the retreat of the Iraqi army in the final phases of the 1991 Gulf War (El-Baz and Makharita 1994).

The establishment of a lingering physical landscape of mines designed to influence maneuver in war remains a particularly hazardous byproduct of modern military action. The presence of mines and unexploded ordinance remaining after conflict tends to keep additional anthropogenic activity from disturbing the terrain, but the potential for continuing military and civilian casualties remain high. Minefields have been emplaced in nearly every conflict since their first recorded use in 1403 (Schneck 1998) and remain one of today's most dangerous landscape legacies of warfare. The United Nations (UN) estimates that 100 million post war mines and unexploded ordinance remain in 90 countries around the world, causing 26,000 casualties per annum (United Nations 1996). Egypt for example, estimates the number of mines in that country alone exceeds 23 million (Human Rights Watch 1999; United Nations Mine Action Service 2000). Afghanistan is similarly affected (Saba 2002).

The United States Department of Defense (DoD), as a federal land steward, actively pursues mediating physical landscape alteration by military operations,

particularly in the U.S., but also worldwide. Geographers and geomorphologists are readily employed. For the length of the Cold War, the United States diligently paid reparations to the Federal Republic of Germany and other NATO allies for maneuver damage caused during annual Return of Forces to Germany (REFORGER) exercises, and others. In 1997, the U.S. government established an Office of Humanitarian Demining Programs to provide expertise, equipment, personnel and funding to assist countries worldwide with demining programs (State Department 1997). Elaborate environmental remediation plans currently exist at all U.S. Army maneuver posts. The National Environmental Policy Act of 1969 (NEPA) and Army Regulation AR 29-00-2 require minimization of any significant short or long-term environmental impacts on natural resources. The Integrated Training Area Management (ITAM) program, designed to insure maneuver terrain is maintained within prescribed standards for use well into the future (Department of the Army 1998), was initiated in 1995 at a cost of $35 million (Doe, Shaw *et al.* 2000; Herl 2000; Thompson 2000) and is an integral part of every Major Army Command's (MACOM) mission strategy. Other recent mitigation efforts include phasing in 'Green Ammunition' that replaces the lead core of small caliber rounds with environmentally benign tungsten in an effort to mitigate potential groundwater pollution (Lillie, Corbett *et al.* 2002), as well as similar initiatives.

Regardless of attempts at mitigation, military operations will continue to alter natural terrain well into the future in both cultural and physical realms, and will likely be of greater magnitude as the destructive capability of armies increase. These changes provide significant opportunities for study. Research addressing the impact of military

operations on desert geomorphology, for example, provides important contributions to efforts mitigating the destructiveness of training exercises and war as well as civilian activities. Military activities are well documented and their often-widespread and long-term alterations to the physical landscape provide a wealth of data.

This study concerns anthropogenic damage to desert areas. In general, human encroachment in deserts increases erosion potential from the action of both wind and water, limits vegetation growth, and decreases soil infiltration capabilities (Milchunas, Schulz *et al.* 1999). Alteration of desert pavement in particular, produces long-term changes because of the landform's inherent stability. The ubiquity of desert pavement and the preponderance of military activity in arid regions will likely lead to repeated vehicle incursions. This study may be useful in assessing management strategies for both military and civilian use of these areas.

Desert Pavement

Desert pavement is an armored surface of abundant, closely packed stone fragments of pebble to cobble size that are only one or two stones thick, set on or often in matrices of finer sediment material several centimeters to meters thick (Mabbutt 1977; Elvidge and Iverson 1983; McFadden, Wells et al. 1987; Thomas 1989; Cooke, Warren et al. 1993; Thomas and Goudie 2000). The closely spaced surface particles protect underlying fine material from further erosional forces, thus earning the name of 'desert pavement' or 'desert armor'. The sediment layer is usually characterized by low infiltration rates arising from surface crust formation under raindrop impact and washing

of fine sediments into near-surface pores. Occasionally, salts act as a bonding agent (Cooke 1970; Cooke *et al.* 1993). The armored layer, although resistant to further erosion by wind and water, can be fragile and may be easily broken when weight is applied to the surface. A human walking on the surface can break the layer of accreted pebbles and sediment matrix and reveal the loosely held fine particles beneath. This results in a scar in the pavement.

Desert pavement occurs extensively in deserts, but is also present in mountain, arctic and periglacial regions (Cooke 1970). They are commonly found atop alluvial deposits in deserts, including alluvial fans and fluvial terraces worldwide (Cooke 1970), but all desert pavements are not categorically similar. Researchers divide pavements into two major types: hamadas, composed of larger rocks, and regs, made up of smaller clasts. The difference is one of human perception along a continuum, so there is no clearly defined division. Regardless, the widespread occurrence of desert pavements around the world has generated a variety of vernacular names depending on where they occur (Table 4-2). Hamadas are rocky, boulder-strewn surfaces where bedrock outcrops dominate (Cooke *et al.* 1993) and are often associated with underlying bedrock (Mabbutt 1977). Reg surfaces are dominated by finer particles and may be underlain by a soil (Mabbutt 1977). Regs cover large areas of the southwestern United States, the Sahara Desert and

Table 4-2. Ubiquitous desert pavement earned several names in different cultural regions.

Location	Name
North Africa and the Middle East	Hamada (Arabic 'unfruitful'). Dominated by bedrock outcrops. Reg (Arabic 'becoming smaller'). Dominated by small size gravels. In the Sahara, Reg is referred to as *serir*.
Australia	Gibber Plains or Stony Mantles
United States	Desert Pavement or Desert Armor
Great Britain	Stone Pavement
Central Asia	Gobi
Asia	Saï

the interior of Australia (Scott 1992). This study considers only the small particle desert pavement, or reg.

Formative Processes

The concentration of coarse particles at the surface of desert pavement is commonly attributed to the work of the wind (Cooke 1970). Physical geography and geology texts at the college level consider eolian winnowing of the fines to be a major process in the formation of the pavement landscape (Walther 1891; Easterbrook 1969; Leet *et al.* 1978; Gabler, Sager *et al.* 1991; Scott 1992; Christopherson 1994; Strahler and Strahler 1994). Despite the prevalence of these opinions, conclusive evidence that deflation is a primary process responsible for the formation of all desert pavement is rare (Cooke 1970) and contradicted by the presence of rock coatings such as rock varnish that would be easily removed by abrasive winds (Dorn 1998). Indeed, scholars do not agree

Table 4-3. Theories of particle concentration in the formation of desert pavement

Process	Mechanics	Source
Deflation	Fine grain material is removed from the surface by eolian forces, leaving behind coarser debris as a lag deposit. Deflation pavements are characterized by clasts lacking rock varnish, because varnish is soft enough to be eroded by abrasive winds.	Cooke (1970) Dan, Yaalon *et al,* (1982)
Water sorting	Fine grain material is winnowed by surface wash.	Sharon (1962) Cooke (1970) Dan, Yaalon *et al,* (1982)
Upward migration of coarse particles	Alternate wetting and drying and associated swelling and shrinking of fine grained material beneath the surface forces larger particles upward. When shrinkage occurs, the coarse material does not return to its former location, which is occupied by fines.	Springer (1958) Jessup (1960) Cooke (1970) Dan, Yaalon *et al,* (1982)
	Freeze-thaw (perhaps limited to high altitude deserts) and salt solution and recrystallization cycles work similar to wet-dry cycles migrating coarse material upward.	Cooke (1970; 1993) Cooke and Warren (1973)
Accretion	Pavement is formed at the surface and lifted as windblown silts and clays accumulate below the coarse gravels.	Mabbutt (1979) McFadden, Wells *et al,* (1987) McFadden (2001)
Subsurface weathering	Increased moisture conditions below the surface favor rock weathering leading to differential weathering rate. A more rapid breakdown of coarse debris occurs in the subsoil environment compared to the desiccated surface.	Mabbutt (1977; 1979) Amit *et al.* (1993) McFadden (2001)

on the origin of desert pavements and identify several methods through which they may be generated (Table 4-3).

Vehicular Effects on Desert Physiography

Increasing infringement on arid lands worldwide spurred considerable research regarding anthropogenic modification to natural systems. Arid lands in the southwestern United States, in particular, are under pressure from increasing recreation use, housing

development, and military training. Thus, it is important to study the effects anthropogenic activities have on fragile desert lands in order to facilitate appropriate environmental management decisions.

Alterations to fragile desert environments by human activity are widespread. The most damaging are related to soil compaction and subsequent increases in erosion rates. Wilshire and Nakata (1976), for example, reported that the annual Barstow to Las Vegas cross-country motorcycle race in the Mojave Desert caused significant soil compaction. Subsequent increases in erosion susceptibility are thought to be the dominant undesired consequence of the race on the landscape. Iverson *et al.* (1981) noted a decrease in soil porosity and infiltration capacity from off-road vehicle use. Webb and Wilshire (1983) presented a full range of research on the impacts of civilian off-road vehicle traffic in the California deserts. They found that off-road vehicle use accelerates water and wind erosion (Gillette and Adams 1983; Hinckley, Iverson *et al.* 1983 see also Marston 1986), has a negative impact on desert soil stabilizers (Wilshire 1983), and results in a negative effect on desert vegetation and wildlife (Brattstrom and Bondello 1983; Bury and Luckenbach 1983; Lathrop 1983). One of the most significant and long-lasting effects of vehicle use in the desert is compaction of the underlying sediment, which changes density, porosity characteristics and infiltration rates (Webb 1983). Soil compaction is a widely cited undesirable alteration (Wilshire and Nakata 1976; Iverson *et al.* 1981; Braunack 1986b; Braunack 1986a; Ayers, Shaw *et al.* 1990; Lovich and Bainbridge 1999; Prose and Wilshire 2000).

Studies dealing with military maneuvers in deserts commonly concentrate on the general effects tracked vehicle movement has over a variety of desert land surfaces. Braunack (1986a), believed that track movement decreases soil strength, increases surface micro-relief, increases bulk density and decreases saturated hydraulic conductivity of soils. He also concluded that ruts are normally formed in the landscape after passage of a tracked vehicle. Ayers (1994) reported that soil compaction, vegetation loss and subsequent increased erosion occurred from passage of a M113 Armored Personnel Carrier (APC), concluding that the track does considerably more damage while turning than moving in a straight line.

A few studies specifically document the effects of vehicle movement on desert pavement, although many of the same effects noted above are relevant. Vehicles easily disrupt desert pavement despite its relative natural stability (Wilshire and Nakata 1976; Elvidge and Iverson 1983). Tanks break and submerge surface stones, overturn surface material, and churn up unvarnished pebbles from the subsurface (Krzysik 1985). The weight of armored vehicles causes compaction of the subsurface (Prose and Wilshire 2000).

Prose and Wilshire (2000) conducted a thorough investigation of the lasting effects of military movement across desert pavement. They investigated relic tank track scars from the same military maneuvers that this study considers (circa 1940-43), and track scars from later exercises conducted in 1964. They compared soil compaction (through use of a penetrometer), soil bulk density, surface reflection, surface clast size, infiltration rates and plant cover and density. They concluded that desert pavement

regeneration was probably not vigorous enough to heal track scars without a climatic shift to wetter conditions; that soil density is greater under the 1940s era track scars despite the heavier weight of tanks in 1964; and that water infiltration rates under track scars is up to 55% lower than under undisturbed pavement.

Regeneration rates for desert pavement are not well known, and thus recovery times from tracked vehicle incursions are similarly uncertain. Works considering regeneration rates of desert surfaces from anthropogenic causes make long-term estimates (Table 4-4).

Table 4-4. Estimated natural recovery times for various desert landscapes and vegetation after anthropogenic disturbance

Disturbance	Recovery Time	Reference
Military base camps	Not recovered after 54 years	Nichols and Bierman (2001)
Road traffic	Partial recovery in decades	Elvidge (1982) Elvidge and Iverson (1983)
Tank tracks (vegetation)	65 years	Lathrop (1983)
Tank tracks (Biological soil crusts on desert pavement)	2000 years	Belnap and Warren (2002)
Base camps (vegetation)	45 years	Lathrop (1983)
Main military roads	100 years – infinity	Prose and Metzger, (1985) as cited in Lovich (2001)
Off-road vehicle use	Probably Centuries	Webb (1983)
Foot trails	1000 years	Von Werlhof (1987)
Intaglios	Over 2000 years	Silverman (1990)

The Butler Pass Study Site

The study site for this research is an interfluve on the gently sloping surface of an incised alluvial fan issuing from Butler Pass in western Arizona (Figure 4-1). The pass rests at approximately 520 meters in elevation. Mean January temperature at Needles, California, 208 km to the northwest, is 11 degrees C and 35 degrees C in June. Rainfall varies considerably from year to year with an annual average of 112 mm at Needles (Prose and Wilshire 2000). Rainfall during 1942-1944 was normal (Prose and Wilshire 2000), but there is no way to tell if track scars were made on dry or wet pavement. The area is covered by well-developed desert pavement consisting of angular granitic, gneissic, and quartzite clasts.

The pass constitutes key terrain in the military sense, providing significant advantage to either friendly or enemy forces that control it. Because of its military importance, it is likely the pass was used extensively during military maneuvers that prepared US Army tankers to fight in World War II, and perhaps, during subsequent exercises 20+ years later (Prose and Wilshire 2000). Numerous track scar pairs appear on the interfluve in a pattern that suggests an approach from the east (the direction of the nearest military base camp), congregation for resupply or maintenance on site (indicated by oil cans and tank parts discarded in nearby wadis), and exit toward the west (the direction of the tactically important Butler Pass summit).

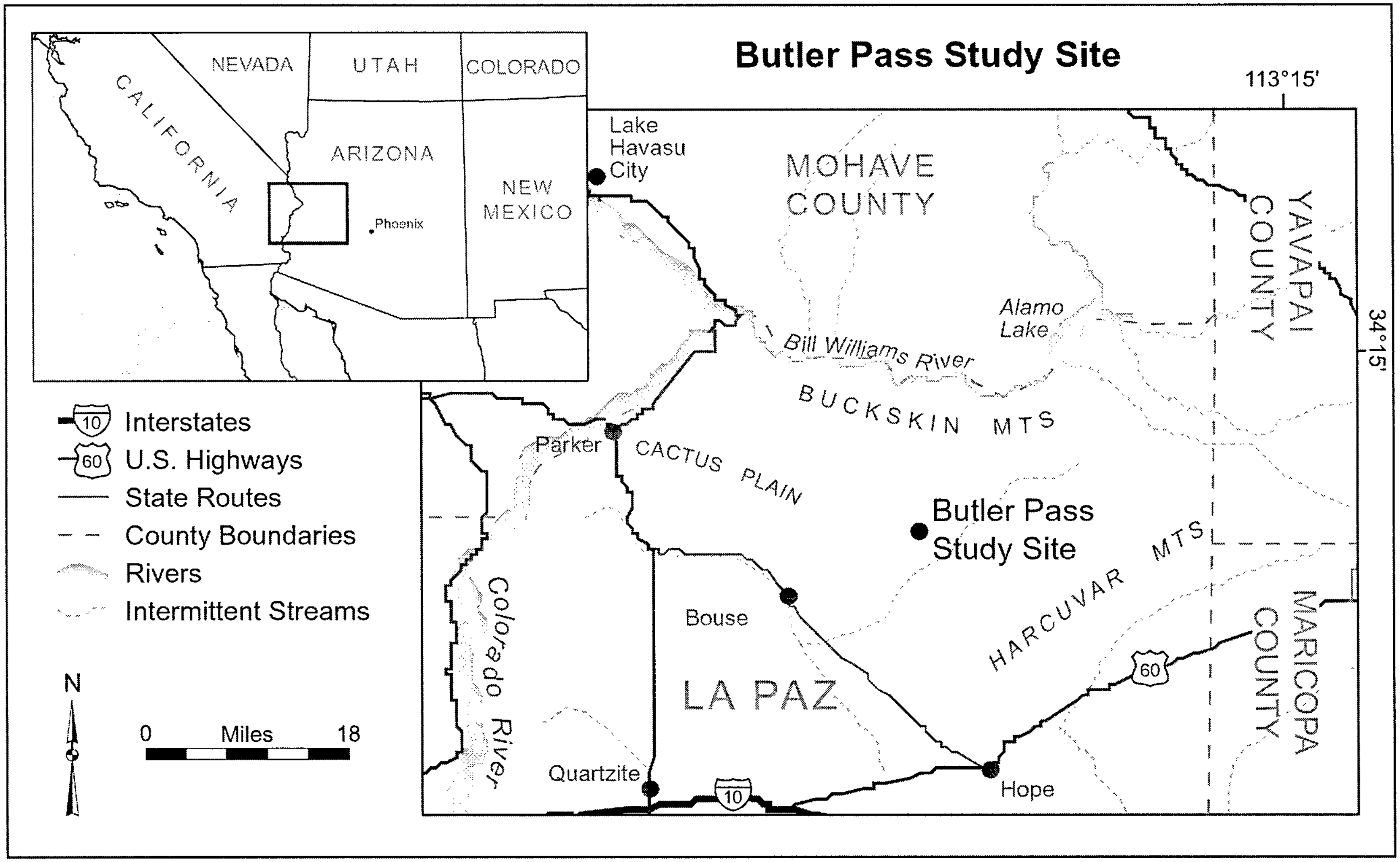


Figure 4-1. The Butler Pass Study Site is located in western Arizona and is accessible by dirt roads While some track scarred pavement is visible from nearby trails, a four wheel drive vehicles is required to gain access to the best preserved tracks.

Butler Pass is part of a training area established in April of 1942 to prepare U.S. soldiers to fight in North Africa during the early years of World War II (Bischoff 2000). Congress set aside over 18,000 acres in California to serve as an armor training site for I Corps. By 1943, the Army greatly extended the maneuver area to allow the establishment and exercise of a "theater communication zone" along with the "combat zone" already in existence. It changed the name of the facility from the "Desert Training Center" (DTC) to the "Desert Training Center / California-Arizona Maneuver Area" (C-AMA) to better reflect its purpose (Bischoff 2000) (Figure 4-2). The study site at Butler Pass lies within the C-AMA.

The study site within Butler Pass was carefully chosen based on specific criteria: the site exhibits extensive and well-developed desert pavement; the pavement is repeatedly scarred by tank tracks; and other than a power line over 100 meters away, the region does not appear to be subject to significant anthropogenic damage other than from relic tank maneuvers. The location's connection to the DTC/C-AMA allows one to reasonably deduce the vehicle type causing each pavement scar under study and to estimate within months the timing of pavement damage.

Especially important is the site's geomorphic uniformity. The surface of desert pavement within the study site consists of uniform clast size and composition; vegetation is uniform throughout the interfluve; the slope is similar; the Av and B horizon in undisturbed areas display uniform characteristics (Appendix A); and the entire site is only several hundred square meters in area near a single interfluve, a sufficiently small size to be confident that geomorphic processes working on the site are similar. Geologic

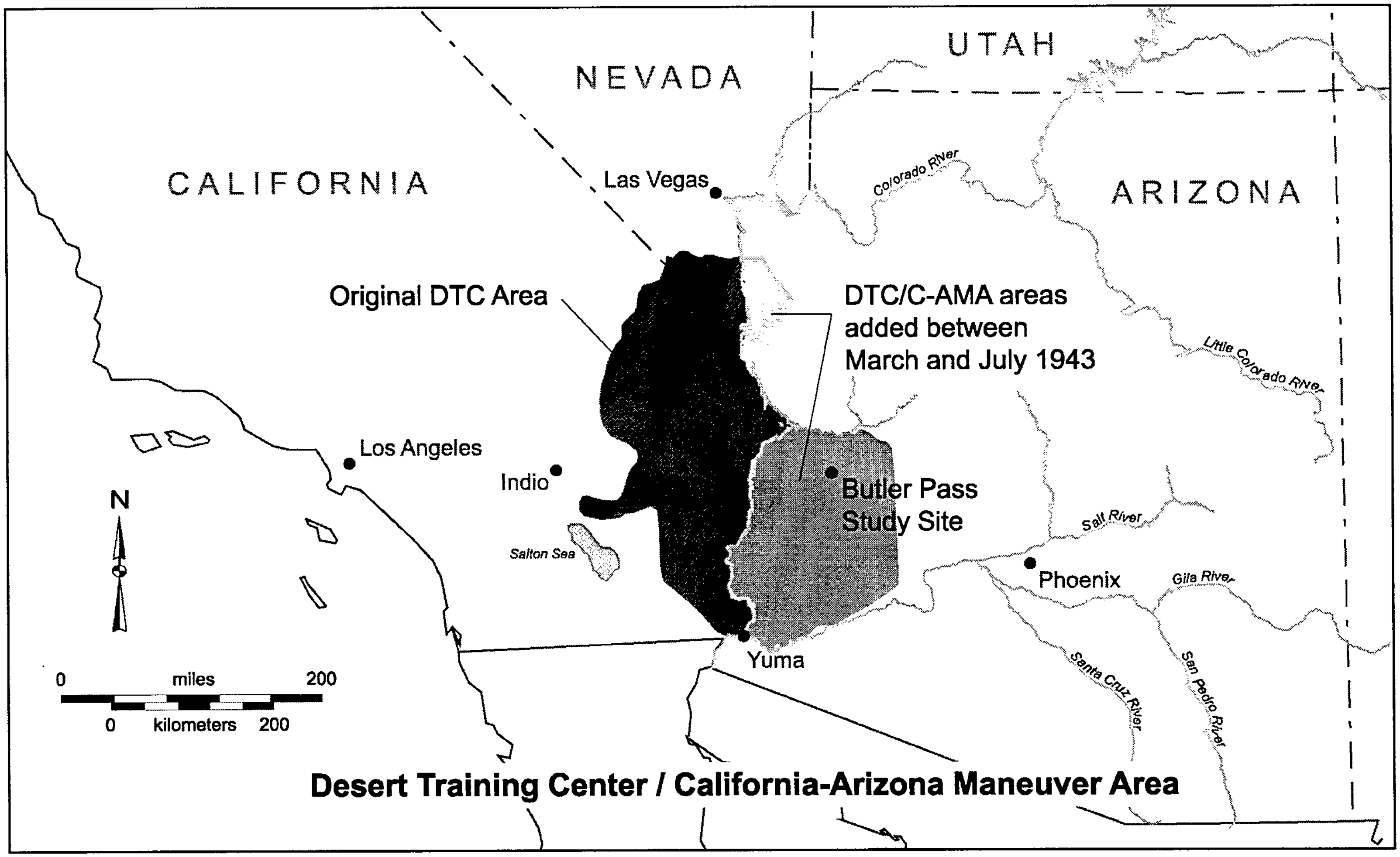


Figure 4-2. The Desert Training Area / California-Arizona Maneuver Area (DTC/C-AMA) was originally established in April 1942 to prepare I Corps soldiers under General George S. Patton Jr. for warfare in North Africa. The training area initially was wholly contained in California, but was expanded in 1943 to include portions of Arizona.

lithology is uniform and there exists no evidence that would indicate a difference in composition within the study area (Figure 4-3).

The study site occurs on a gently sloping (1-2 degrees) alluvial fan of Pleistocene age, based on pavement characteristics and soil development (cf. Bull 1991). Pavement stones range in size from less than 1 cm^2 to over 20 cm^2 in surface area exposed to sunlight and cover virtually 100% of the surface, except where broken by slopes or natural gullies. Clasts are largely made up of quartzite, granitic and gneissic particles, many of which are varnished except in areas of track scarring. The Av soil horizon beneath the pavement surface clasts is indurated such that removal of a pebble reveals a sharp indentation of the pebble surface in the sedimentary matrix. The indentation can be destroyed by finger pressure, but not without some effort.

Tank tracks through the pavement are numerous and easily distinguished from undisturbed areas (Figure 4-4). They appear as a slight depression, are lighter in color than surrounding undisturbed pavement, and are generally in identifiable pairs at equal distances apart. The clasts within track scars appear smaller than in the undisturbed areas.

The unmistakable scars that a turning tank leaves are unique and easily identified to one familiar with tracked vehicles. Wheeled vehicles characteristically leave 'tracks' or scars from all four wheels when turning, tracked vehicles leave only two. Track scars characteristically have a buildup of debris on the outside of the turn because the track slides across the surface with the leading edge gouging out surface material and piling it along the track's edge. Wheeled vehicles may also leave debris ridges, but of less

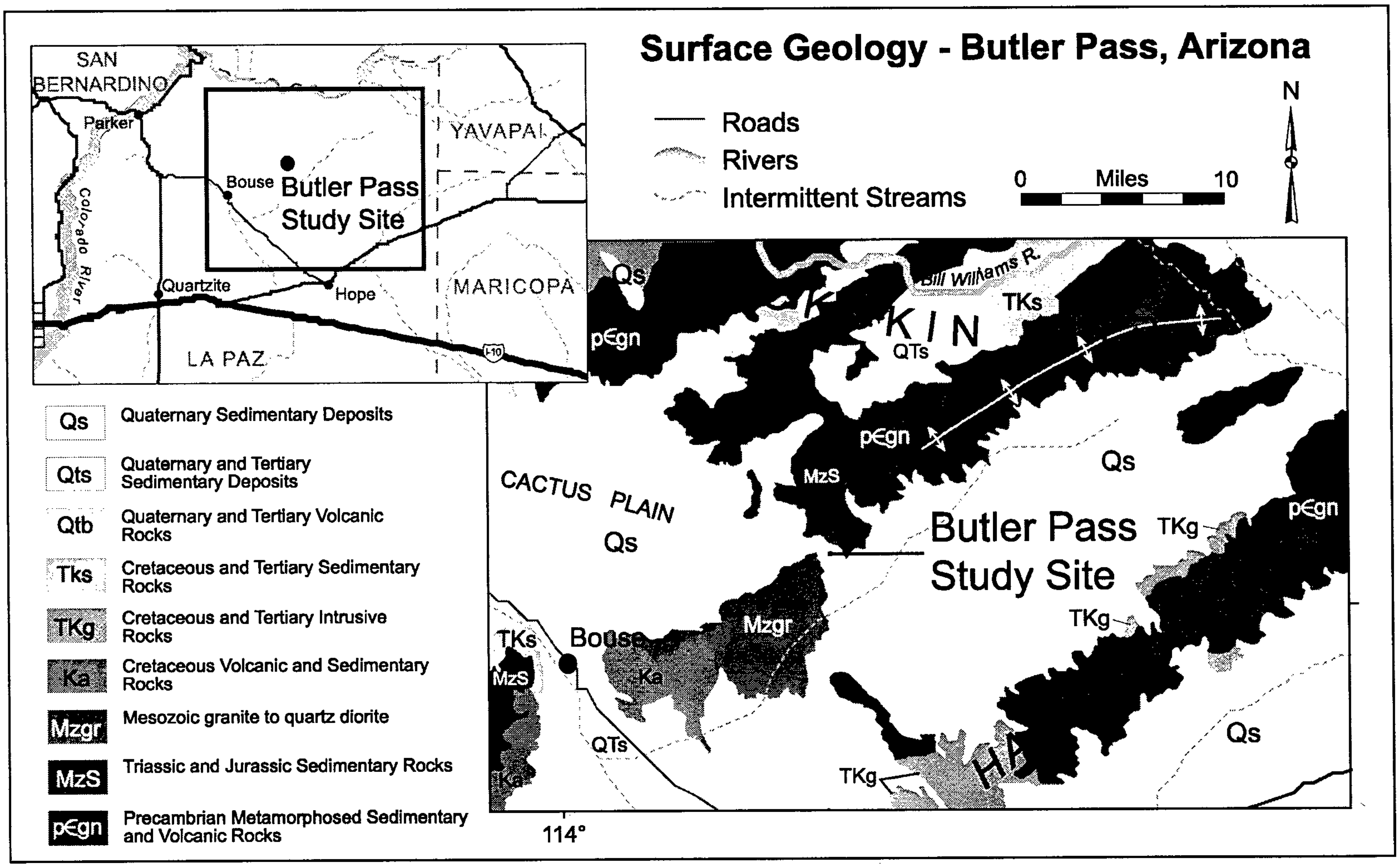


Figure 4-3. Geologic map of the Butler Pass Study Site.

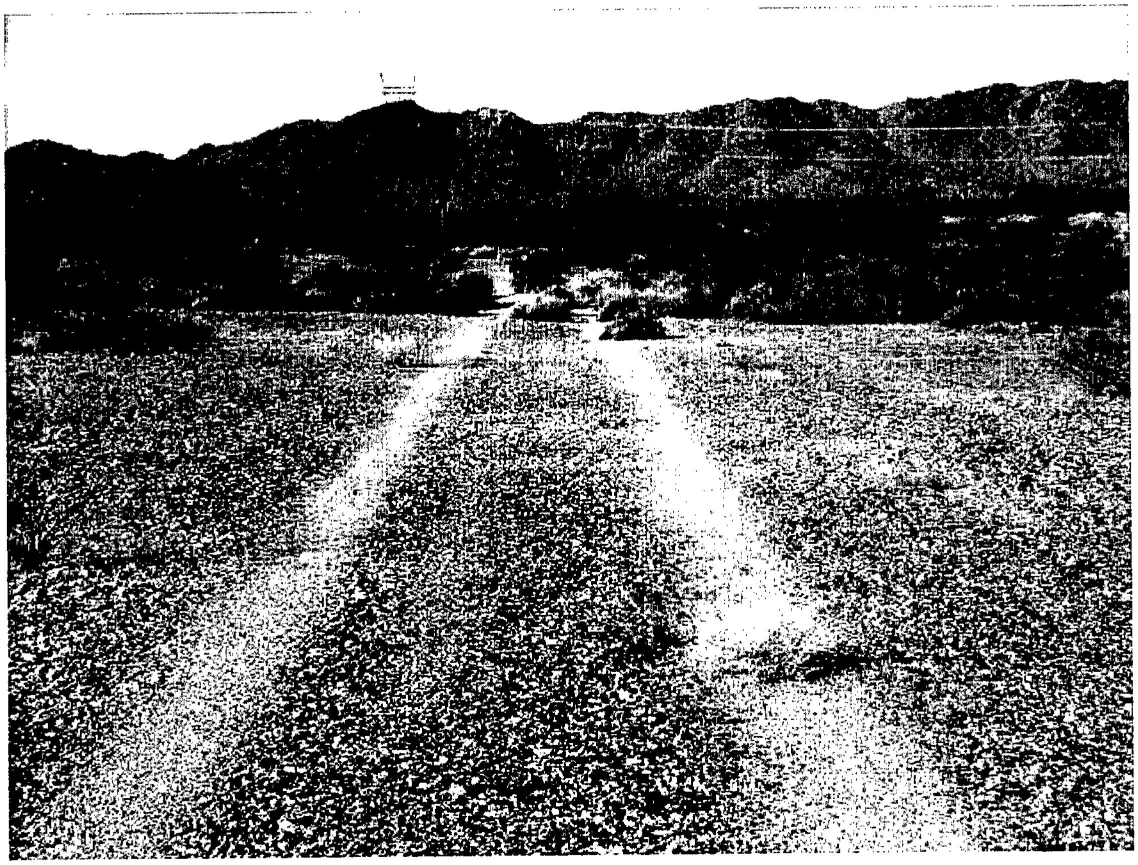


Figure 4-4. World War II era track scars are clearly discernable on the well-developed desert pavement at the study site.

volume. Normally these ridges are created by only the front two wheels. Track scar width becomes wider in a tracked vehicle turn because of surface sliding that takes place; wheel scars do not generally increase in width if the vehicle is turning. Track scar width is 7-25 cm wider than wheel widths and track scar base (the distance between track pairs) is 46-152 cm greater.

Methods

There exist obvious differences between scarred and undisturbed pavement at the study site. This research initially compares differences quantitatively and qualitatively then uses this information to assess the relative strength of regenerative processes. The next section describes the selection process used to determine track scars analyzed in this research. The impact of tank passage is examined through surface observations including albedo, particle size, mass, density, volume and sphericity. Surface induration, rock coatings and microtopography are also examined, as well as subsurface attributes including depth of the Av horizon and moisture penetration, sediment size, structure and soil density.

Track Scar Selection

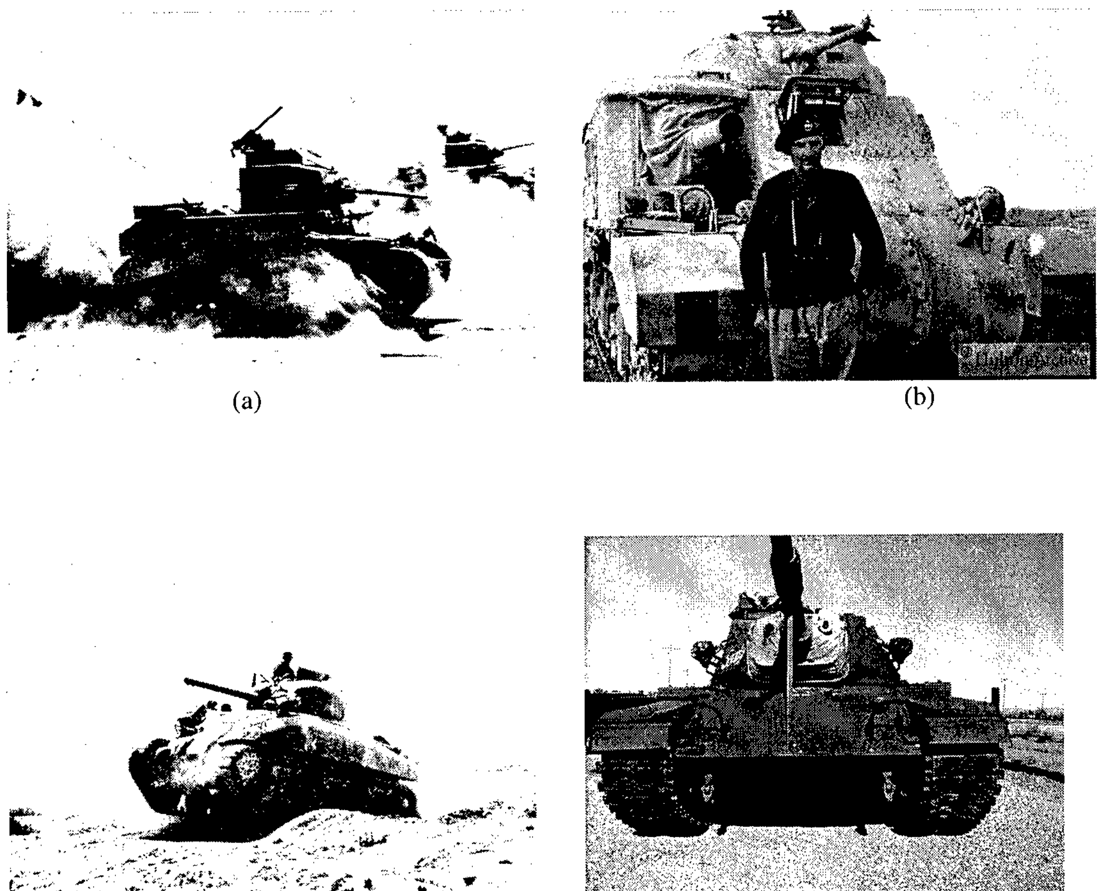
Not all track scars within the research site are good candidates for study. Tracks made by turning vehicles disturb the surface in a variety of ways that cannot be held constant or accounted for. Multiple passes by tanks moving in column affect soil compaction. Track scars studied in this research are straight-line passes by single tracks

of known vehicle type and model. For a track pair to be considered appropriate for study, it meets the following criteria:

1. Tracks must be clearly discernable for at least 5 m in length.
2. The track pair must maintain a track base length consistently over 2 m wide and the width of individual tracks must be over 25 cm.
3. A single pass of a single track must create the scar. This criterion is satisfied if the track scar turns at some point beyond the segment being studied. Scars made by two or more vehicles moving in column can be identified by a much wider turn scar than a single track.

A critical task is to correctly identify the vehicle types that created track scars under study to insure field data are valid and to establish a creation date. Tanks in the Army inventory and maneuvering in the study area in the early 1940s were the M3A1 Stuart, the M3A5 General Grant Tank, and the M4 Sherman (Bischoff 2000) (Figure 4-5a, b, c). The majority of tanks using the DTC/C-AMA in 1943/44 were M4s. A second exercise, "Operation Desert Strike" was also run in the vicinity of the Butler Pass study site in 1964 (Prose and Wilshire 2000). Tanks used at that time were the M60 MBT (Main Battle Tank) (Figure 4-5d), which differ considerably in vehicle weight, ground pressure, track width and track base from the World War II era vehicles (Table 4-5).

A detailed series of measurements insures track scars analyzed meet reasonable track base and width criteria for military tanks. Since track scar edges in the study site are not clearly defined because of their age, track width and track base measurements at 10 cm intervals were subjected to a one-sample t-test comparing these measurements to specifications from all tracks listed in Table 4-5.



(a) (b) (c) (d)

Figure 4-5. Tanks maneuvering in the Butler Pass area during the last 60 years include (a) the M3A1 Stuart Light Tank, (b) the M3A5 General Grant Medium Tank, (c), the M4 Sherman Medium Tank, and (d) the M60 Main Battle Tank. (a) (Jablonski 1977) (b) (Hulton Archives 2003) (c) (Jablonski 1977) (d) author.

Table 4-5. Vehicle Characteristics. Measurement convention for track base is from the outside of one track to the outside of the other. This makes the value useful in calculations concerning track transport on rail or ship where space is a prime factor.

Vehicle	Track Width	Track Base	Vehicle Weight	Ground Pressure
M3A1 Stuart Light Tank (a)	29.5 cm (11.6 inches)	2.24 m (88 inches)	12,900 kg (12.7 tons)	.91 kg/cm^2 (12.9 lb/in^2)
M3A5Grant Medium Tank (a)	40.6 cm (16 inches) or (b) 42.1 cm (16.6 inches)	2.72 m (107 inches)	28,100 kg (27.7 tons)	.89 kg/cm^2 (12.7 lb/in^2)
M4 Sherman Medium Tank (a)	42.1 cm (16.6 inches)	2.62 m (103 inches)	30,300 kg (29.8 tons)	1kg/cm^2 (14.3 lb/in^2)
M60A1 Main Battle Tank (c)	71.12 cm (28 inches)	3.63 m (132 inches)	57,406 kg (56.5 tons)	.87 kg/cm^2 (12.37 lb/in^2)
For Comparison (c): Civilian 4x4 Dodge Dakota	(Wheel Width) 22.86 cm (9 inches)	(Wheel Base) 1.78 m (70 inches)	2,430 kg (2.7 tons)	Not Available

(a) Information from onwar.com/tanks/usa, accessed 17 September 2002.
(b) Measurements vary depending on track type.
(c) Measured by author (M60A1 Tank is located on display at Bouse, Az).

Surface Observations

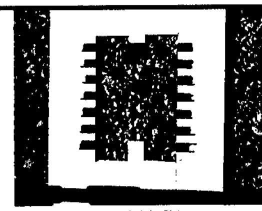
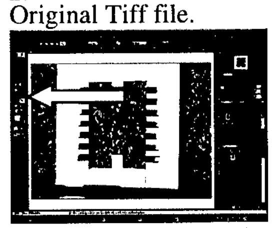
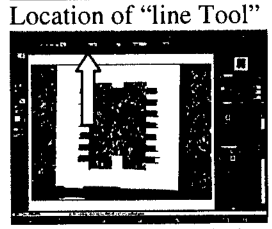
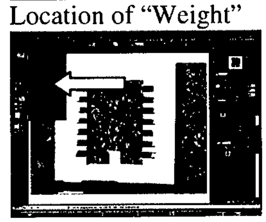
Differences between in-track scar surface material and that of undisturbed out-of-track surface material are obvious to even the casual observer. Stones inside track scars are much smaller and are lighter in color than those constituting the surrounding pavement. They are not engulfed in a matrix of indurated sediment, as are stones in undisturbed areas. These observations provided the justification for more detailed analyses in this section.

Albedo and Surface Particle Area: Digital image processing quantifies both surface albedo and particle area (the area of a surface stone that can be seen from above,

or that is exposed to sunlight) to allow comparison between surfaces inside track scars and those on undisturbed pavement. I established transect pairs along seven track scars, one inside the scar and one parallel to and outside of the track scar (on undisturbed pavement approximately 10 cm from the scar boundary). Digital photos, including flat black and flat white calibration tabs and a cm scale were taken at 20 cm intervals along each transect until a total of 34 photos were available (Figure 4-6). Use of a camera tripod maintained relatively constant focal length between images. Photos were imported into Adobe Photoshop 6.0 and checked to determine the number of pixels per cm. The appropriate scale was then set in the software and a 10 cm line was generated using the software scale. This allowed a comparison to be made between the cm scale preserved in the digital photo, and the 10 cm line generated in the software, to check accuracy. If the scale was within 2 mm, the photo was accepted and saved. If not, it was rescaled. A subset of the image was then used in both albedo comparison and surface particle size measurement (Table 4-6 and Figure 4-7).

Albedo: Histograms of each digital image provide an albedo comparison between surfaces inside and outside of the track scars. The image is first cropped to the 2 cm width of the calibration tabs and the 10.25 cm distance between the calibration tabs (Figure 4-7). The cropped image is then calibrated where black is set to a value of 0 and white to 255. A new image is delineated using the rectangle tool to capture the entire image except the calibration tabs. A histogram of the resultant area provides the mean

Table 4-6. Image preparation in Adobe Photoshop.

Steps	Location on Screen	What to do	Purpose	Example
Import Image	Toolbar under File menu, labeled 'Open'	Select and Open TIFF file	Imports TIFF file for use in Adobe Photoshop	 Original Tiff file.
Activate the line tool	Drawing toolbar	Click "Line Tool".	Activates the 'Line Tool' which brings up a pixel weight option at the top of the page	 Location of "line Tool"
Set Scale	Top of the screen labeled "Weight"	Choose an appropriate line weight, draw a line and compare its width to the cm scale in the image. Use a 10 cm length.	Determines the exact image scale.	 Location of "Weight"
Prepare to crop Image	Drawing Toolbar	Click "Rectangular Marquee Tool" and outline area of interest.	Prepares image for cropping	 Location of "Crop"
Crop Image	Main toolbar	Click "Image", then "crop"	Crops image	 Cropped image
Save Results	Main toolbar	Click Toolbar under "File", then "Save As"	Saves image	 Saved image

value of reflectance for each image (between 0 and 255), which are recorded for import and into MS Excel and Statistical Package for the Social Sciences (SPSS) (SPSS 1998) (Appendix B).

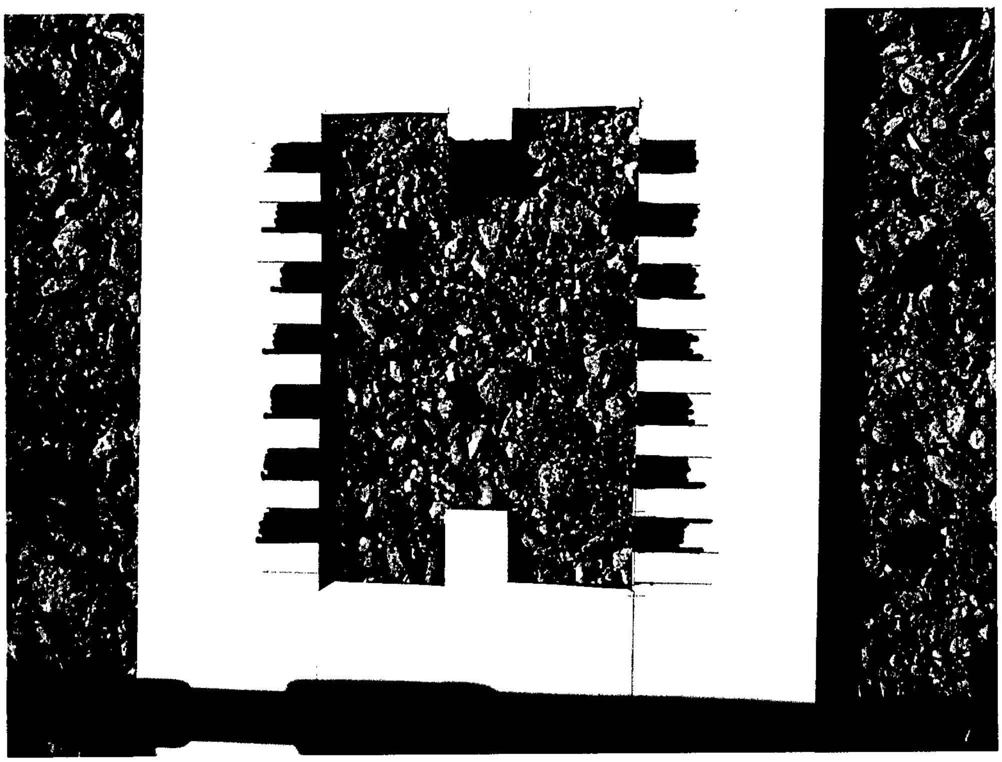


Figure 4-6. One of 34 digital image pairs used to compare track-scarred surfaces with undisturbed pavement surfaces. This image is of a track-scarred surface. The black and white calibration tabs are at the top and bottom of the frame.

Figure 4-7. The image in Figure 4-6 is cropped to include the black and white calibration tabs. This image is rotated 90 degrees to fit conveniently in the manuscript.

These values are then tested for normality using visual inspection of histograms, standard error of skewness and kurtosis (Siegel 1956; Keeping 1962; Granger 1979), and the Kolomogrov-Smirnov test (Kolmogorov 1941; Smirnov 1948; Massey 1951; Birnbaum 1952; Birnbaum 1953; Dixon 1954). I then compared in track and undisturbed pavement albedos using an independent samples t-test in SPSS (SPSS 1998).

Surface Particle Area: Because the cropped image (Figure 4-7) is of a known size and scale, the area of the image is also known. Nearly 100% of surface areas are covered with clasts. It is therefore possible to count the total number of clasts in each image and divide this number into the total area of the cropped image to get a mean sunlight-exposed area for each stone. The results are then tested for normality using visual inspection of histograms, and standard errors of skewness and kurtosis (Siegel 1956; Keeping 1962; Granger 1979). I compared values using an independent samples t-test in SPSS (SPSS 1998).

Surface Induration: Induration of the upper soil matrix is common to desert pavement (Cooke 1970; Dixon 1994), yet the intensity of crustal formation is difficult to measure. A simple qualitative assessment is possible at Butler Pass because a large difference exists in the level of induration between scarred and undisturbed pavement surfaces. I removed a large surface clast from the undisturbed pavement surface, recording the indentation left in the surface crust in digital photos. Removal of similar particles from track scars leaves no such indentation. I used finger pressure to move the friable surface of scarred pavement and recorded this indentation in digital imagery for

visual comparison. I also conducted the NRCS Field Book method for field testing soil consistence. I used rupture resistance and manner of failure tests (Schoeneberger, Wysocki *et al.* 1998) to compare the in track surface consistence to undisturbed pavement conditions.

A more accurate assessment of surface induration is possible through observation of the relative compactness of the soil matrix. An indurated surface should exhibit a more compact soil matrix than a friable one. Surface compaction was tested in two ways, both of which are described in detail later in this chapter. First, a soil sample of the Av horizon was taken and observed using backscatter electron microscopy (BSE) (Reed 1993) to assess soil matrix porosity. Second, surface soil density was measured using a nuclear density gauge, also utilizing BSE techniques (Troxler Electronic Laboratories 1998).

Surface Particle Mass, Volume, Density and Sphericity: Collection of random samples of surface stones from transect pairs inside the track scars and areas adjacent to undisturbed pavement provide comparable data. I collected samples using a 10 x 10 cm framed grid. The grid size is limited to insure it fit fully inside the track scars. The grid frame contains centimeter markings and crisscrossed matrix guidelines.

A random number generator (Dackombe and Gardiner 1983, 217) provides coordinates to select 34 stones at each location. The first digit provided by the random number generator indicates a gridline on the x axis of the frame, and the second digit indicates a gridline on the y axis. Stones are chosen under the grid intersection

designated by these random number pairs. In the rare instances when a grid intersection does not fall squarely on a stone, the nearest stone is chosen. I initially took samples inside track scars, then repeated the process for an adjacent area outside of the track scar and far enough away to insure the area had not been influenced by the track movement (approximately 20-50 cm).

Samples are weighed, and their volume is measured using water displacement in a graduated cylinder. Stone volume and density provide complementary measurements to two dimensional sunlight-exposed area assessments. Desert pavement stones are embedded in a matrix of sediment and a significant portion of the stone may be hidden from view, and thus not accounted for using area assessment. I calculated average particle density by dividing the sample mass by its volume.

Samples are next measured with calipers. Particle measurement allows calculation of Maximum Projection Sphericity (MPS) (Sneed and Polk 1958). Particle size and form are the major contributors to particle resistance to transport (Goudie, Lewis *et al.* 1981), and provide another indicator of particle stability that complements other methods used in this study. Since the perfect sphere has the least surface area of any three dimensional solid and therefore offers the least resistance to transport, a stone with a high MPS should be less resistant to movement.

MPS calculation requires three measurements to be made for each stone: the longest dimension (L); the intermediate dimension (I); and the shortest dimension (s). Each of these measurements are mutually perpendicular, but may not meet at the same point (Sneed and Polk 1958). The formula to determine MPS is:

$$\sqrt[3]{s^2/LI}$$

This measure compares the particle's maximum projection area, defined as the product of the L and I axis -- and also the surface area opposed to the direction of motion -- with the maximum projection area of a sphere of the same volume (Sneed and Polk 1958). I tested the values for normalcy using visual inspection of histograms and standard errors of skewness and kurtosis (Siegel 1956; Keeping 1962; Granger 1979). I then compared the values using an independent samples t-test in SPSS (SPSS 1998).

Rock Coatings: A variety of different types of rock coatings exist in the study area, but the most visually dominant is rock varnish. Rock varnish provides an indication of surface stability, demonstrating, for example, that aeolian abrasion does not occur or occurs with relatively little strength (Dorn, 1998), or that particle mobility exceeds the pace of varnish accumulation in the study area. A preponderance of coated pebbles indicates that a surface is more stable than one that does not display as many rock coatings.

I used the Palmer Rock Coating Index (Palmer 2002) as a guide to quantify the number and types of rock coatings in each of the surface images. I drew a transect longitudinally through the middle of each cropped 2 cm by 10.25 cm image and visually examined surface particles intersecting the transect to identify its rock coating (either rock varnish, iron skin, or no coating). The strength of the rock coating is observed and weighted between 1 and 4, where 4 represents the most strongly coated particles, and 1 represents minimal or no surface coating (Table 4-7). These weighted values are

Table 4-7. Rock coating index (after Palmer 2002).

Coverage	0-25%	26% - 50%	51% - 75%	76% - 100%
Value Assigned	1	2	3	4

correlated in a matrix with the three possible rock coating types – manganese dominated, iron oxide dominated, or no coating (Appendix C).

Microtopography: Tank movement across desert pavement crushes indurated surfaces and compacts the soil (Krzysik 1985; Prose and Wilshire 2000). Resultant track scars appear to be slightly lower than undisturbed pavement surfaces (Braunack 1986b). I measured the depth of track scars by using a level and ruler to record the deepest point of each scar (Appendix D). Since track scars meeting suitability criteria for study are straight-line passes, debris berms along the side of ruts do not often affect these measurements. However, it is not possible to eliminate the influence of berms alongside the ruts, and their presence increases depth measurements slightly.

Subsurface Observations

Initial observations of subsurface sediment are conducted using standard soil profile descriptions (cf Schoeneberger *et al.* 1998; Birkeland 1999) (Appendix A). The state of the Av horizon is of particular concern regarding regeneration processes at work on scarred desert pavement. The top few centimeters under the surface layer of pebbles are made up predominately of silt and clay size sediment that is permeable and filled with vesicles from escaping CO_2 (Birkeland 1999). Presence of an Av horizon indicates that surface water is able to infiltrate the upper portion of the soil profile.

Depth of Av Horizon and Character of the Av-B Horizon Boundary: The Av horizon at the Butler Pass study site appears to be a slightly lighter color (Munsell 7.5 YR 4/4) than the darker, redder B horizon (Munsell 5 YR 4/6). This boundary is sharp (Birkeland 1999) and is measured using a ruler. I measured Av horizon depth both in and out of track scars, then created a plan view of the Av-B horizon boundary, a technique rarely used in previous literature. I used a horsehair brush to carefully remove approximately 25 cm x 150 cm area of the Av horizon across the track scar and beyond, including areas not driven on by a tank. I found this easy to accomplish even in the indurated undisturbed areas since the wide vesicles (pores) in the Av horizon make it susceptible to removal with little effort after the covering layer of pebbles is eliminated.

Depth of Moisture Infiltration: This part of the study has its foundation in an initial observation that took place after a winter rain event. The depth to which moisture penetrated the subsurface of desert pavement in track scars was observed to be greater than the depth of penetration in adjacent, undisturbed pavement. Prior observations in the literature on infiltration capacity after off road vehicle (ORV) activity (Iverson *et al.* 1981; Webb 1983; Webb and Wilshire 1983; Wilshire 1983; Wilshire and Webb 1983) suggests that these initial field observations are anomalous and deserve more detailed study.

Subsequent observations were engineered by artificial addition of water to the surface. I dug a small trench approximately 1.5 m long, 15 cm wide, and 30 cm deep perpendicular to a track scar. I dug another small trench of similar dimensions a few

decimeters away in undisturbed pavement. A swamp cooler screen was carefully laid 5 cm away and parallel to the trenches. This distance provides a buffer area between the trench side and the area where water is added to the surface so the presence of the trench does not affect moisture penetration. Water was slowly added to the swamp cooler screen, which acts as an evaporation retardant and controls surface water flow so runoff is minimized. A total of 7.6 liters (2 gallons) of water was applied, and the trench was dug back approximately 7 cm to reveal the depth of moisture penetration, which was measured with a ruler.

Sediment Size: A key to understanding possible differences between track scars and undisturbed pavement including permeability and porosity, are differences in sediment sizes with depth. I collected sediment samples at 2 cm intervals down to 12 cm both in and out of track scars. Each sample was oven dried for a minimum of 3 hours, then dry sieved to divide the sample into seven standard sizes (Table 4-8). Sieved sediment components were weighed allowing calculation of proportions (Appendix E). These proportions are then displayed graphically as percentages for qualitative analysis.

Sediment Structure: In order to compare track scar sediment with undisturbed sediment, it is necessary to observe differences with respect to depth. I dug two trenches approximately 1.5 m long, 15 cm wide, and 30 cm deep. One trench was dug perpendicular to a track scar (crossing it) and another was dug approximately 50 cm away in undisturbed pavement. I sculpted the trench side to create a 45 degree slope, then blew the slope face with compressed air to eliminate foreign dust contamination. I then poured

epoxy down the slope and allowed it to cure. The resultant sediment specimen (approximately 6 cm wide, 3 cm deep, and 10 cm long) was then pried out, turned over, and a second application of epoxy was applied to the back side. I carefully wrapped the specimen and carried it to the lab where I applied another epoxy coat to the entire sample. I then cut each sample with a rock saw longitudinally and epoxied the new edges. I used a rock saw to cut small samples at various depths. These samples were encased in an epoxy cylinder and progressively polished with smaller grit sizes, the smallest being 0.5 micron.

The samples were then coated with carbon and analyzed with a JEOL 8600 Electron Microprobe using backscattered electron (BSE) imagery. BSE microscopy detects electrons that are scattered, where atoms with higher net atomic number are brighter (Reed 1993). A BSE detector therefore, provides good compositional contrast and can be used to clearly distinguish sediment structure at scales of 1 micron to 100 microns and beyond. Contrasting textures in BSE images, when used in tandem with X-

Table 4-8. This table cross-references common grain sizes (top row) with standard sieve sizes recommended by the American Society for Testing and Materials, Standard E-11 (ASTM E-11) and the Wentworth-Phi scale. The ASTM and Phi scales denote the proper sieve size that should be used to isolate sediment by grain size. After sieving a sediment sample with sieves listed in the table, the remaining material that falls through the finest sieve is classified as silt and clay.

	Gravel	Very Coarse Sand	Coarse Sand	Medium Sand	Fine Sand	Very Fine Sand
ASTM E-11 Scale	#10	#18	#35	#60	#120	#230
PHI Scale	-1	0	1	2	3	4

ray dispersive analyses, also distinguish carbonate from silicates in sediment samples. I used the microprobe to image sediment samples taken at approximately 2 cm, 3 cm and 5 cm in depth from the surface of both track scarred pavement and undisturbed pavement.

Soil Density: A common method of determining soil density is through the use of bulk density testing (cf Iverson *et al.* 1981; Braunack 1986b; Prose and Wilshire 2000). However, the presence of innumerable rocks and rock fragments throughout the B horizon prevents collection of suitable samples in the study site location. Another and more accurate soil density measuring method, is the use of a soil density gauge. Soil density gauges are nuclear devices commonly used in construction as a nondestructive and accurate way to determine density and moisture content of soils, aggregate, concrete and asphalt. The gauge determines the density of material through the measurement of gamma radiation in either a direct transmission or backscatter mode (Troxler Electronic Laboratories 1998). The use of a nuclear density gauge is a construction engineering industry standard method (cf American Society for Testing and Materials (ASTM 2002)), but there does not appear to be significant use of these devices in geomorphic work. Limitations include the cost of contracting a licensed user to conduct measurements, or the difficulty and cost associated with training, licensing, and federal security mandates required to buy and manage a controlled nuclear device. Regardless, a nuclear density/moisture gauge provides a nondestructive, rapid and highly accurate method of determining soil density and moisture in the field.

A Troxler model 3430 Roadreader density/moisture gauge determined differences between soil density under track scars and under undisturbed pavement. Backscatter and direct transmission readings were taken at fifteen paired locations (Appendix F and Figure 4-8). The gauge determines soil density at the surface through backscatter of gamma photons emitted at the base of the instrument. These photons must be scattered at least once to reach the detectors in the gage. Denser material therefore, scatters more photons, and the density is calculated by a microprocessor in the gauge. A direct transmission method is used to measure soil density at depth by counting the number of photons emitted by a cesium-137 source rod that is extended through the base of the gauge into a predrilled hole in the soil. Photons from the source rod travel through the soil, colliding with electrons present in the material, and reach the photon detectors in the in the base of the gauge where they are counted. High density soils increase the number of collisions between photons and the electrons present in the soil, therefore reducing the number of photons reaching the detector tubes. High soil density lowers the number of photons reaching the detector. A microprocessor in the gauge converts the photon count into a density reading (Troxler Electronic Laboratories 1998).

Moisture determination occurs through backscatter measurement. A Californium-252 source is located inside the gauge base. Fast neutrons from this source enter the test soils and are slowed by collisions with hydrogen atoms. The helium 3 detector in the gauge base counts the number of thermalized (slowed) neutrons that are backscattered to

the detector and converts that count to a moisture reading (Troxler Electronic Laboratories 1998).

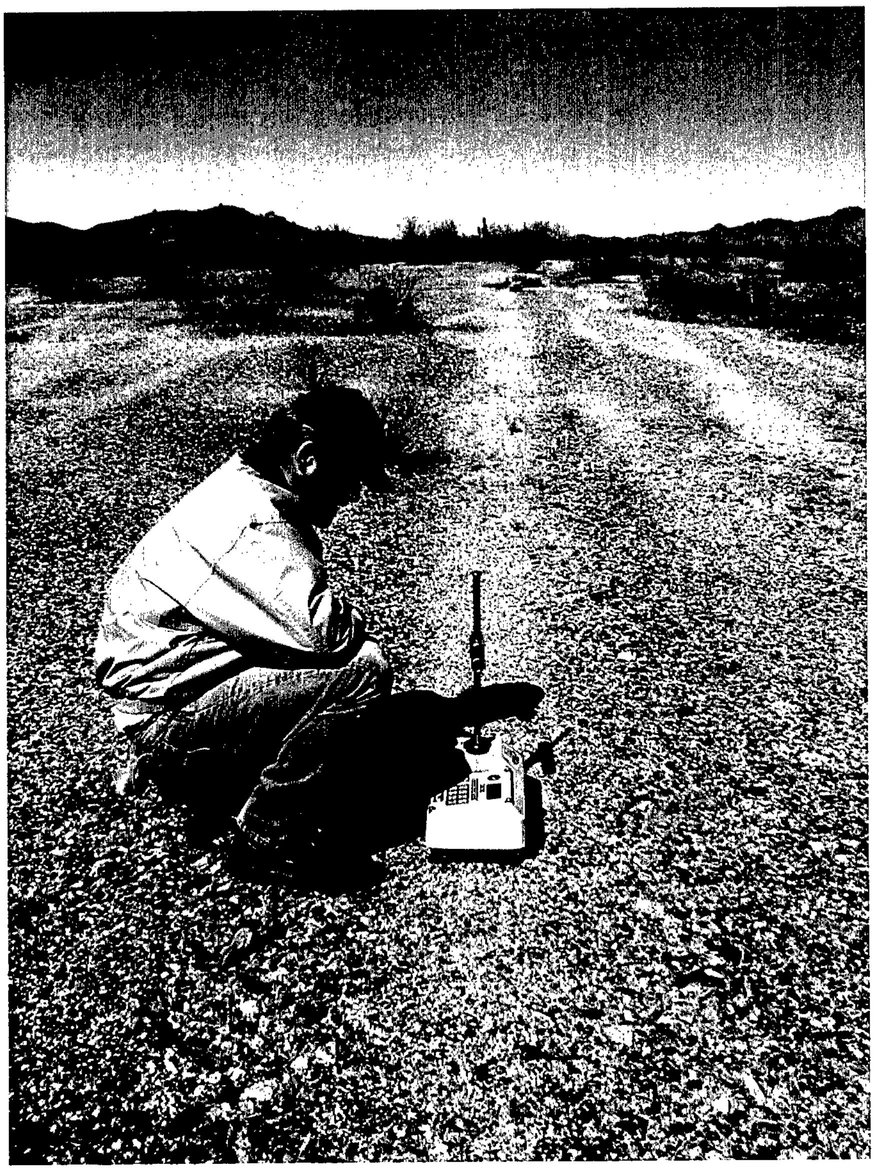


Figure 4-8. The Troxler Roadreader 3430 is a nuclear density gauge that accurately measures soil density and moisture content in a nondestructive manner. The gauge is commonly used by the construction industry and is shown here measuring the density of desert pavement soils under a track scar at Butler Pass

I took measurements every 5 cm (2 inches) in depth under track scars down to a depth of 20.3 cm (8 inches). Each of these measurements is paired with density measurements of undisturbed pavement adjacent to the track scar and not more than one meter away.

Results

Tank Tracks

Measurements of each track scar pair under study are useful in determining what model of tracked vehicle caused the scar, and when the surface alteration occurred. M60 MBT track scars are considerably different from World War II era tanks, being wider in base and width. Track scars investigated in this study correlate most closely with measurements from World War II era vehicles. A total of seven track scar pairs were examined in this study. One tailed t-test results for all track scar widths and bases most closely correlate with the M4 Sherman Tank (Appendix G and Figure 4-9). Tanks operating in maneuvers during World War II did not travel through Butler Pass until 1943 at the earliest. The military maneuver area did not include Butler Pass until it was expanded in March 1943 (Bischoff 2000) (Figure 4-2).

The DTC/C-AMA was officially closed in April 1944, and maneuver exercises curtailed significantly before the end of 1943 (Bischoff 2000). Tank tracks in the Butler Pass area, therefore, must have been made between March 1943 and April 1944. The late summer months of 1943, when the DTC/C-AMA experienced its most active period (Bischoff 2000), is the most likely period of pavement scar formation. Investigation of

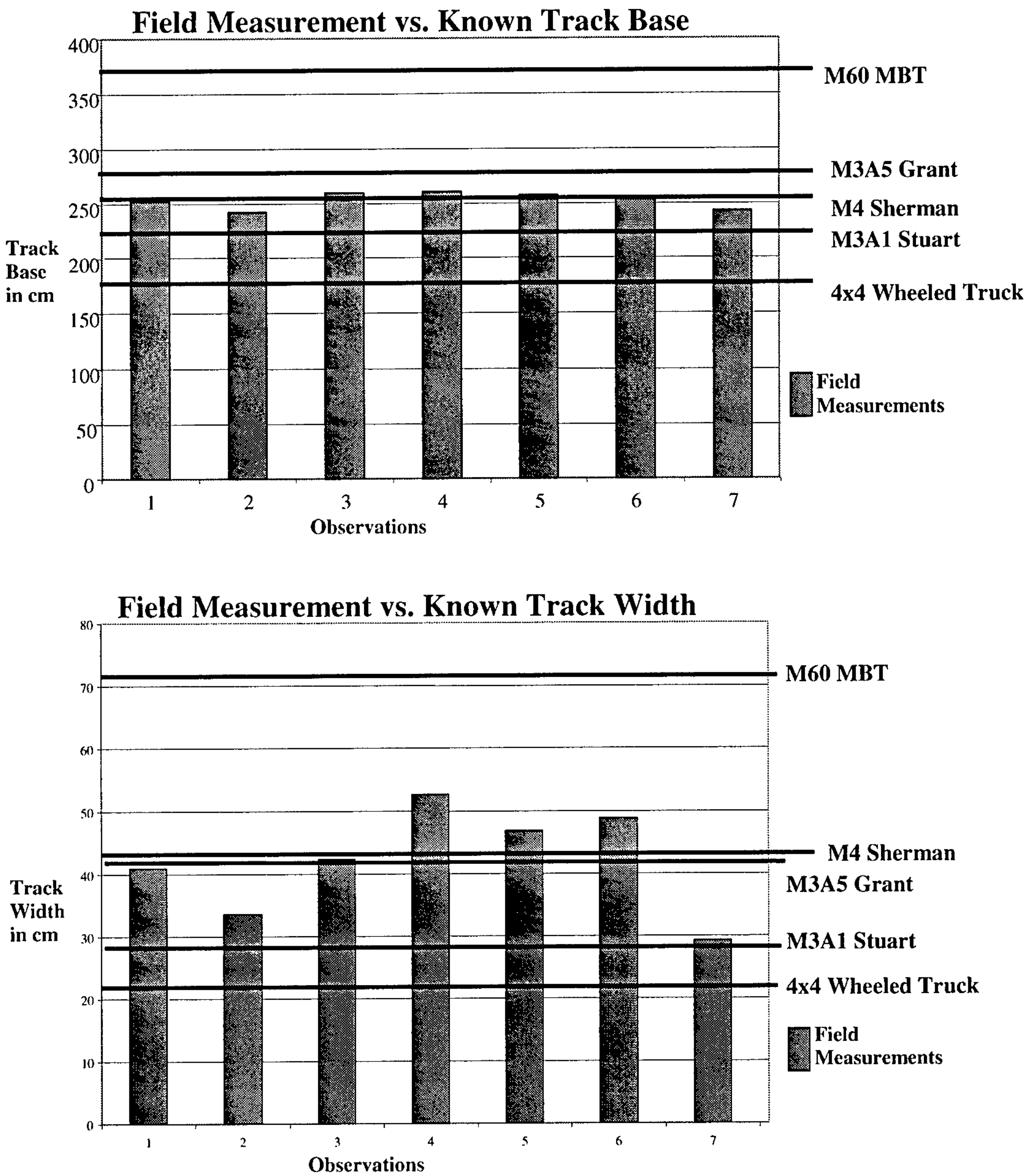


Figure 4-9. Comparison of known track base distances *(a)* versus track scar base; and known track widths *(b)* versus track scar width measured in the field most closely correlate with World War II era tanks.

debris found in a gully within 100m of the tracks examined in this study, revealed 5-gallon oil cans commonly used by the Army for tank maintenance, and tank parts including M4 track end connectors. The date stamped on the bottom of the oil cans is 24 May, 1943 (Figure 4-10). No track scars in the study area matched M60 MBT or 4x4 wheeled vehicle dimensions.

Surface Observations

Albedo: The average albedo (luminosity) value for surfaces inside track scars is 99.4 and it is 78.1 for undisturbed areas on a scale of 0 (black) to 255 (white). I evaluated albedo data for normality using the standard coefficients of skewness and kurtosis (Siegel 1956; Keeping 1962; Granger 1979) (Appendix B). In both instances, the skewness and kurtosis values indicate no statistically significant deviation from a normal distribution. I then conducted an independent samples t-test to determine statistical significance of this difference, which is significant at the 95% confidence interval (Appendix A and Figure 4-11).

Surface Particle Area: Surface particle area data for particles in track scars and those on undisturbed pavement were evaluated for normality using the standard coefficients of skewness and kurtosis (Siegel 1956; Keeping 1962; Granger 1979). Skewness and kurtosis values between 1.96 and –1.96 are considered normally distributed. In the case of surface particle area on undisturbed pavement, the standard error of skewness and kurtosis values indicate no statistically significant deviation from a

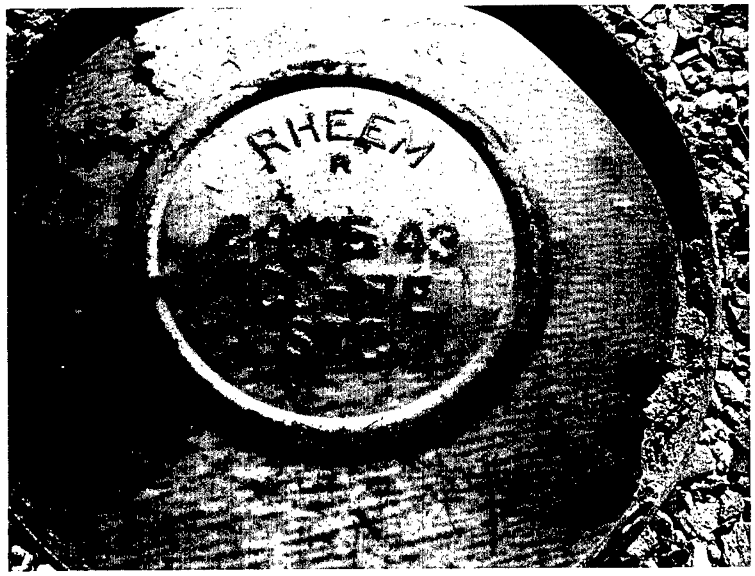


Figure 4-10. This oil can was discovered in a wadi bounding the study site along with other debris including M4 track end connectors. The date stamped on the bottom of the oil can is "24-5-43" (24 May 1943).

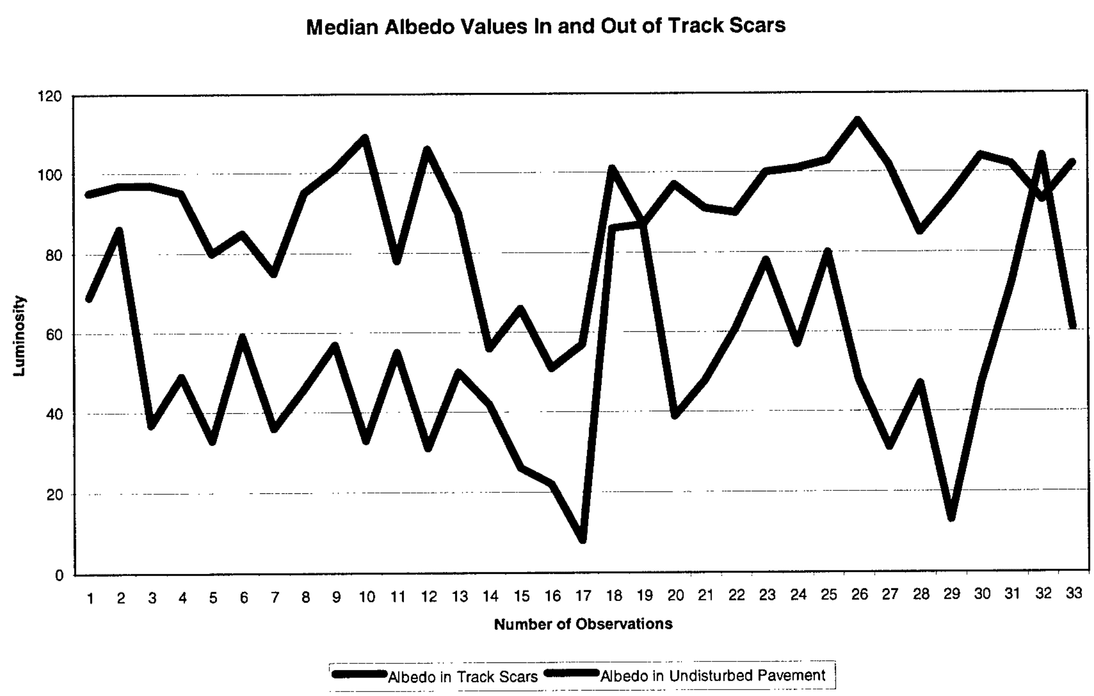


Figure 4-11. Comparison of median surface albedo values. Luminosity is scaled 1-255 with Black = 0 and White = 255.

normal distribution. The standard error of skewness for in track particle area data, however, was 2.161 and the kurtosis value was 5.461, indicating that the null hypothesis (that the in track particle areas are normally distributed) could be rejected. Noting the small n (33) for this test, I then evaluated the data for normality using the Kolmogorov-Smirnov one sample test (Kolmogorov 1941; Smirnov 1948; Massey 1951; Birnbaum 1952; Birnbaum 1953; Dixon 1954). This test analyses each variable against another variable having a normal distribution. The test is well suited for data sets with relatively low sample sizes. The in track scar surface particle area did not have a statistically significant Kolmogorov-Smirnov Z score which would have required the rejection of the hypothesis that the observed data follow a normal distribution. In summary, both in track and out of track surface particle area data are normally distributed (Appendix H).

Having established normality for both in and out of track scar surface particle area data sets, I then compared them using an independent samples t-test (SPSS 1998). The values are statistically significant at the 95% confidence interval (Appendix H). In track surface particle size averages 27.19 mm^2 and surface particle area outside of track scars average 71.6 mm^2 (Figure 4-12).

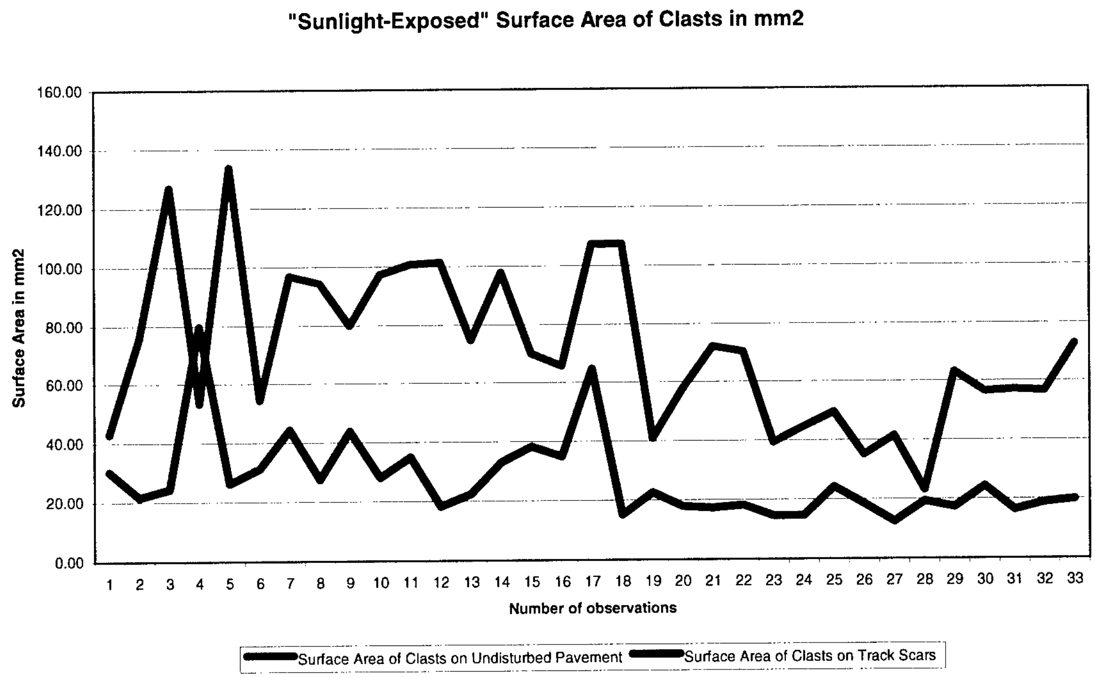


Figure 4-12. Comparison of surface clast area in track scars and on undisturbed pavement.

Surface Induration: Figure 4-13 illustrates differences between the level of surface induration in track scars, where induration is not present, and undisturbed pavement, where induration is relatively strong. NRCS surface induration tests (Appendix A) and BSE imagery support this qualitative data. BSE imagery of sediment samples at the 2 cm depth in undisturbed pavement show considerable compaction of the soil matrix, whereas track scar samples at the same depth are less compact.

(a)

(b)

Figure 4-13. Comparison of surface induration between the surface of undisturbed pavement (a), and the surface of track-scarred pavement (b). The indentation in (a) is from removal of a surface particle suggests strong induration of the Av horizon. Slight finger pressure that moves the much smaller surface particles in track-scarred areas (b) illustrates the friable nature of the surface. Note: images are not at the same scale.

Surface Particle Mass, Volume, Density and Sphericity: Sample particles taken from the surface of undisturbed areas attained a mass of 592.4 grams and a volume of 275 ml. Surface particles inside track scars had a mass of 36.4 grams and a volume of 30 ml. Density of surface particles inside track scars is 12.13 kg/m^3, and undisturbed pavement particles averaged 19.25 kg/m^3. Sphericity of surface stones (Appendix I) in track scars averaged .5984 (1.0 = a perfect sphere). Those on undisturbed surfaces averaged .6074. Sphericity values are not significantly different at the 95% confidence interval.

Rock Coatings: Undisturbed pavement contains more rock coatings than does scarred pavement. Table 4-9 illustrates the relative presence of manganese and iron coatings as a percent of total coatings. Track scars contain cobbles with far fewer rock coatings compared to undisturbed areas.

Table 4-9. Comparison of coated and non-coated surface rock particles in track scars and in undisturbed areas.

	In Track Scars Or Out of Track Scars	# Particles	Not Coated	Manganese Coating	Iron Coating
Total images	34 IN	513	1404	150	80
Total images	34 OUT	266	966	214	123

Subsurface Observations

The Av horizon inside track scars averages 3.6 cm in depth, while undisturbed areas average 2.3 cm (Appendix J). Standard field soil description (Schoeneberger *et al.* 1998; Birkeland 1999) reveals the A-B horizon boundary is rated either 'abrupt' (.5 to < 2 cm) or 'very abrupt' (< .5cm) in track scars and undisturbed areas (Schoeneberger *et al.* 1998) (Appendix A). A more detailed observation is possible through examination of the surface of the B horizon. The Av horizon above both scarred and undisturbed pavement was carefully removed with a horsehair brush to reveal the upper B horizon plane. In undisturbed pavement, the top of the B horizon is distinct, displaying a sharply defined, indurated surface covered with dessication cracks in the form of polygons. Under track scars, no upper B horizon surface emerged, and no dessication cracks are visible (Figure 4-14).

Depth of Moisture Infiltration: Moisture infiltration in and out of track scars varies significantly. I measured clearly defined moisture boundaries under track scars and under undisturbed pavement. The average depth of infiltration is 5.7 cm under track scars and 3.4 cm under undisturbed pavement (Appendix K).

Sediment Size: Results of sediment sieving at 2 cm depths are in Appendix E. Figure 4-15 shows sediment mass as a percent of the total sample mass for each of seven

(a)

(b)

Figure 4-14. Once the Av horizon is removed, a plan view of the Av – B horizon boundary illustrates significant difference between undisturbed pavement (a), and track scarred pavement (left portion of b). Polygonal dissection cracks suggest an abrupt boundary in undisturbed areas, but no cracking or cleanly observable boundary is present under track scarred areas.

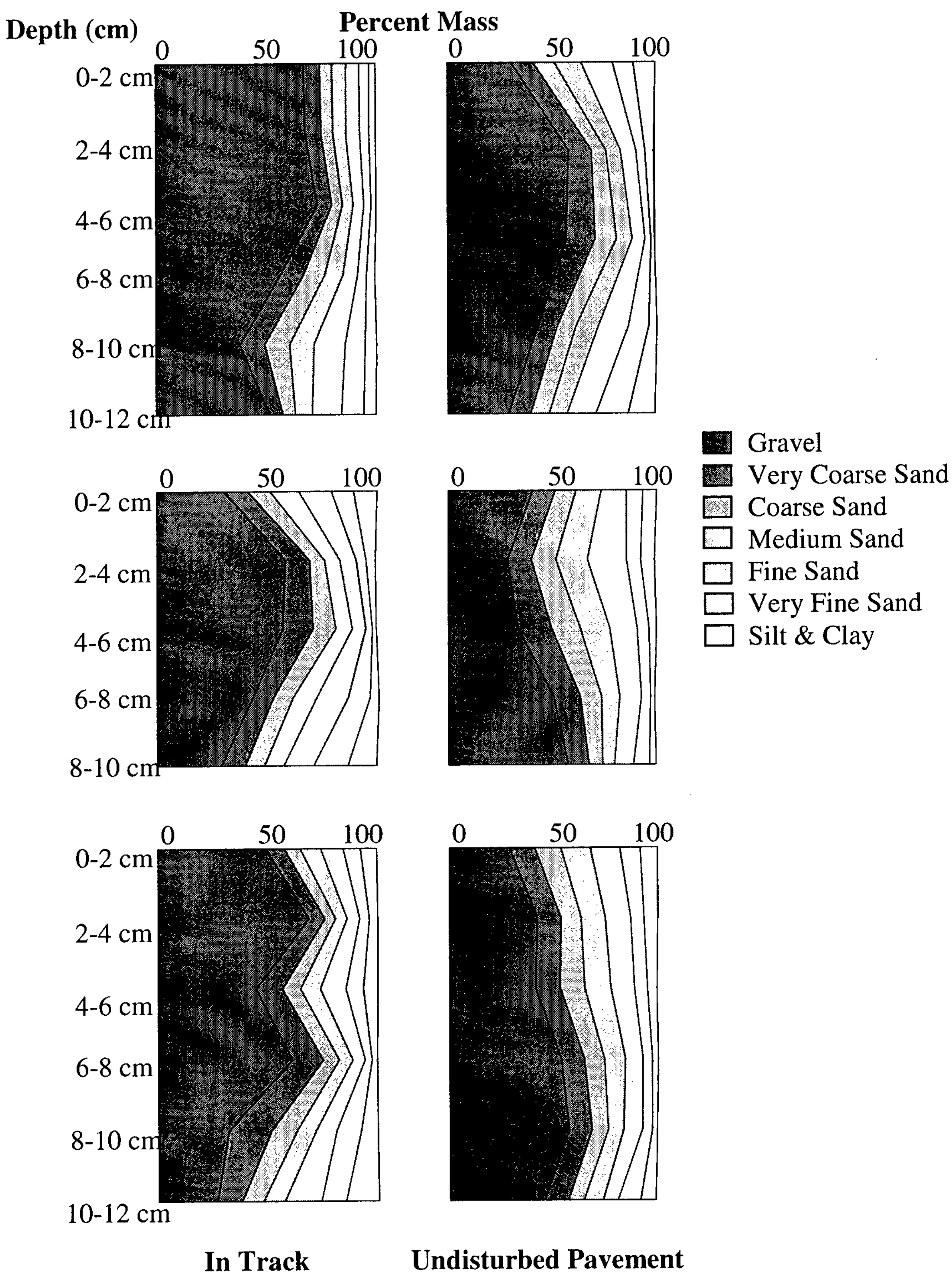
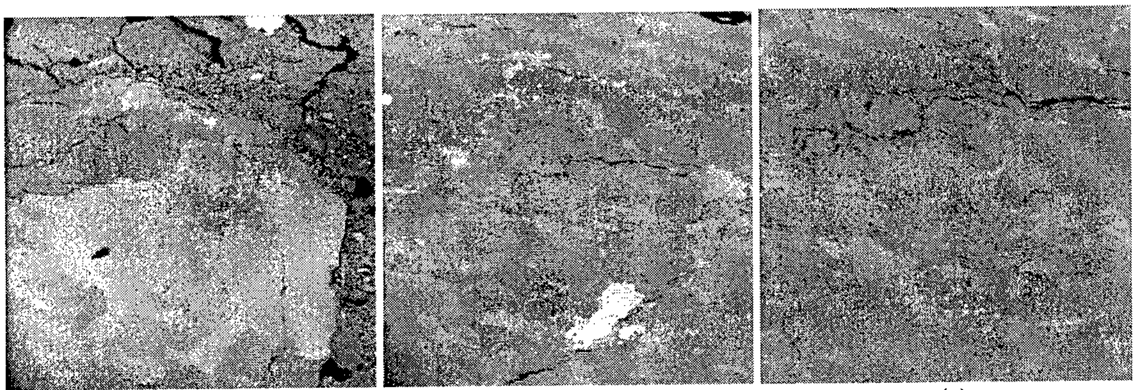


Figure 4-15. Sediment mass with depth.

sediment sizes, with respect to depth. Results are not consistent between sites, but sediments under track scars tend to consist of a larger proportion of smaller sediment sizes (< 2mm) in the upper 4 cm.

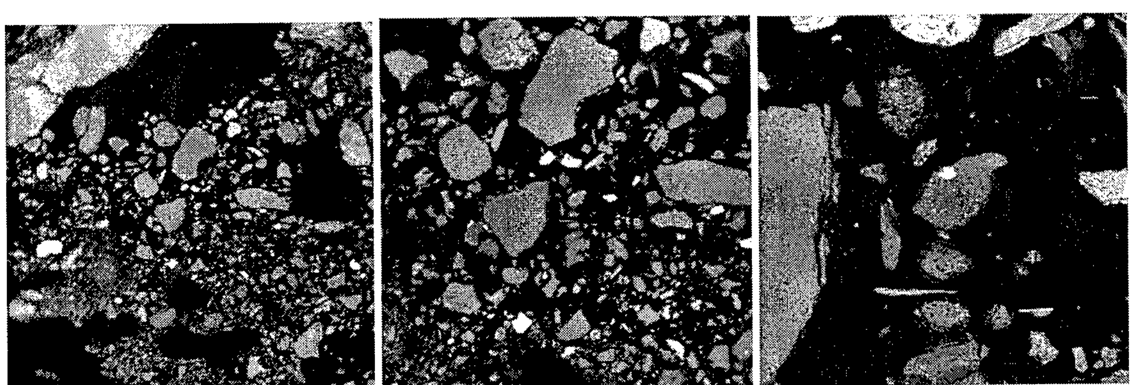
Sediment Structure: BSE imagery provides compositional data that allow qualitative assessments of sediment texture. Samples were taken at depths of 0-2 cm, 3 cm and 5 cm both inside and outside of track scars. Samples at 0-2 cm depths are within the Av horizon in both undisturbed pavement and in track scars. These BSE images display significant differences in the character of soil particles (Figures 4-16 and 4-17). In track scars, the Av horizon sediment appears fractured, whereas undisturbed pavement sediment appears comparatively solid. At 3 cm depth, the trend begins to reverse with comparatively more solid soil plasma for in track samples than at the 0-2 cm depth (Figures 4-18 and 4-19). At 5 cm depth, the soil compaction is clearly opposite of the 0-2 cm samples; more compacted soil textures occur under track scars than in undisturbed pavement (Figure 4-20 and 4-21).

Of particular note is the difference in the character of a pore in the Av horizon (0-2 cm depth sample). Figures 4–22 and 4-23 show what appears to be a tube-like feature; former root channels of plants could readily produce such structures (Birkeland 1999). The former root provides a pathway for water to move through the sediment through capillary action, but the compaction clearly present within the tube's wall makes the sediment appear more impervious to gravity and capillary water movement.



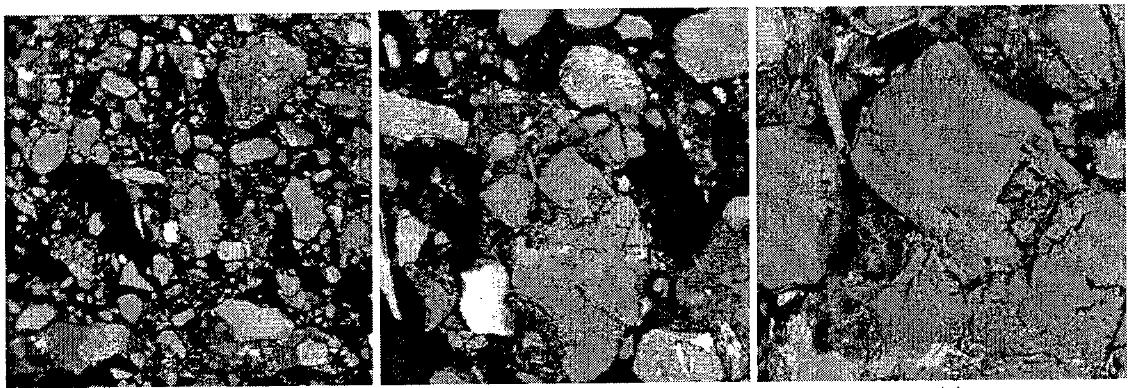
(a) (b) (c)

Figure 4-16. BSE imagery of the Av horizon sediment in track scars between 0-2 cm in depth. The soil plasma at this depth is well compacted with relatively few, small pore spaces. Scale: The width of each image is (a). 600 microns, (b). 600 microns, (c). 230 microns.



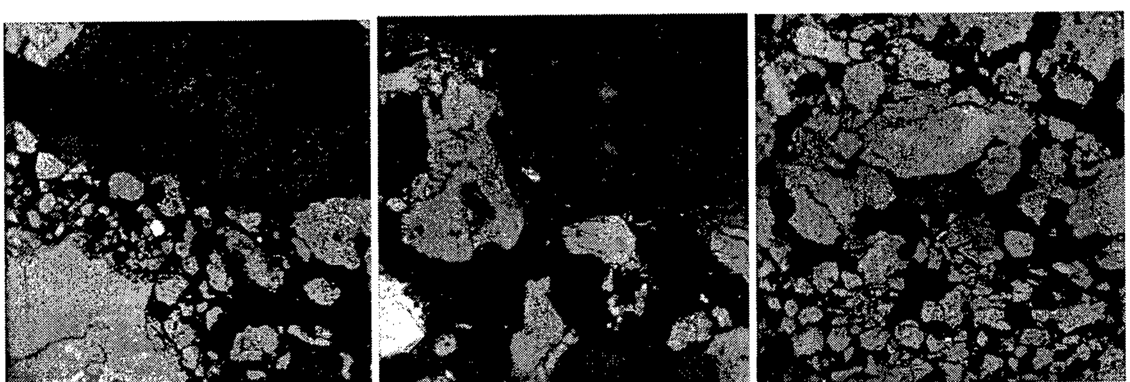
(a) (b) (c)

Figure 4-17. BSE imagery of the Av horizon sediment in undisturbed pavement between 0-2 cm in depth. The soil plasma at this depth possesses large pore spaces. Scale: The width of each image is: (a). 600 microns, (b). 300 microns, (c). 60 microns.



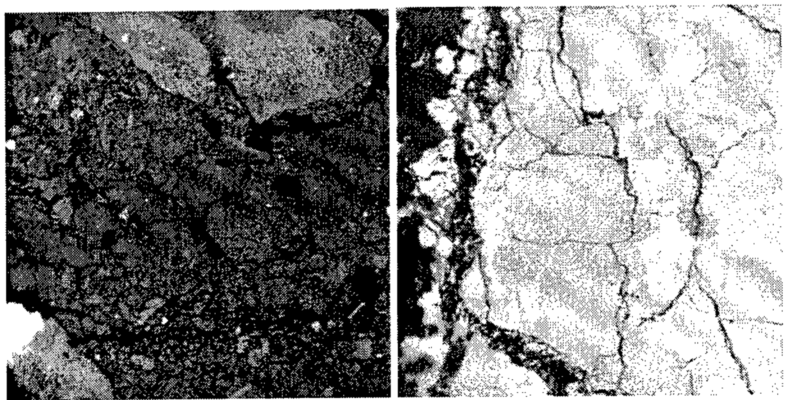
(a) (b) (c)

Figure 4-18. BSE imagery of the Av horizon sediment under track scars at 3 cm in depth. The soil plasma at this depth possesses relatively more pore spaces than at 2 cm depth. Scale: The width of each image is: (a). 2241 microns, (b). 690 microns, (c). 224 microns.



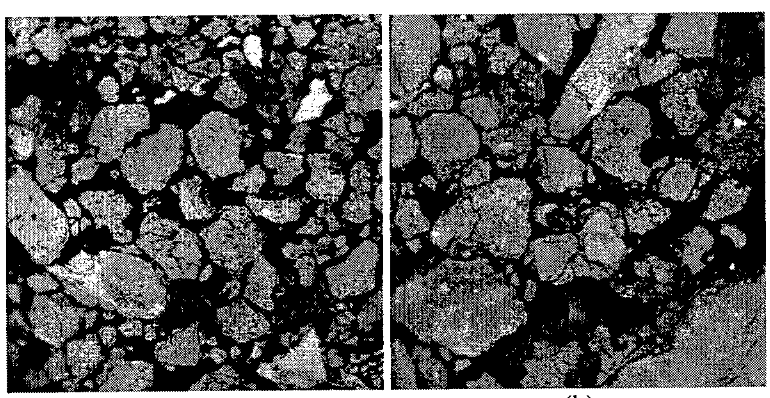
(a) (b) (c)

Figure 4-19. BSE imagery of the Av horizon sediment in undisturbed pavement at 3 cm in depth. The soil plasma at this depth possesses large pore spaces. Scale: The width of each image is: (a). 600 microns, (b). 120 microns, (c). 600 microns.



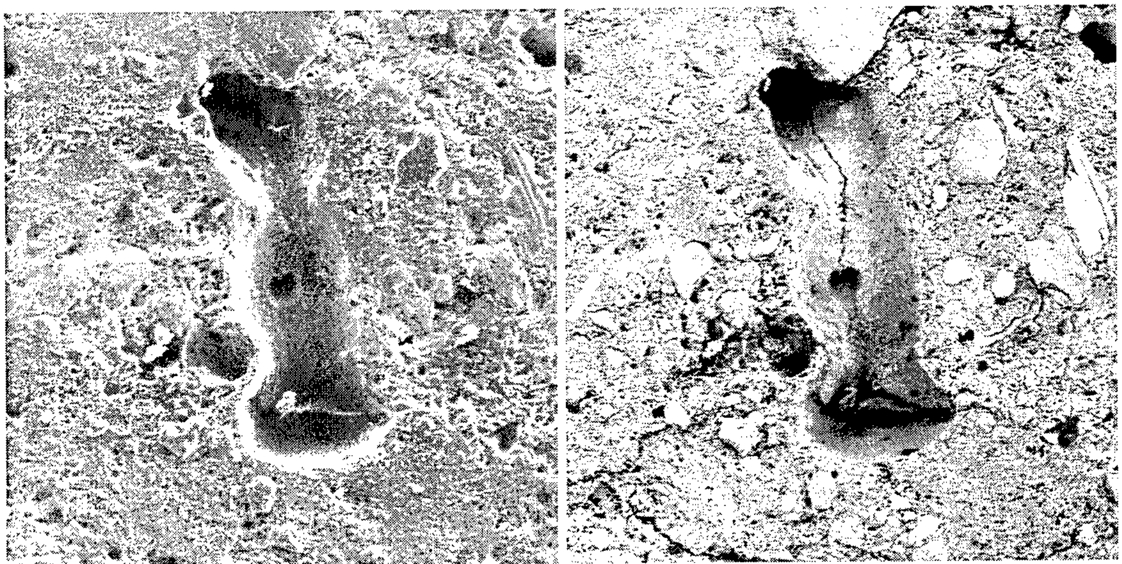
(a) (b)

Figure 4-20. BSE imagery of the Av horizon sediment under track scars at 5 cm in depth. The soil plasma at this depth possesses relatively more compaction than at 2 or 3 cm depths. Scale: The width of each image is: (a). 600 microns, (b). 600 microns.



(a) (b)

Figure 4-21. BSE imagery of the Av horizon sediment in undisturbed pavement at 5 cm in depth. The soil plasma at this depth is relatively more compact than in track samples at the same depth. Scale: The width of each image is: (a). 600 microns, (b). 600.



(a) (b)

Figure 4-22. This large pore space, probably created from a plant micro-root is present in the Av horizon of undisturbed desert pavement. The SEI (Scanning Electron Imagery) view (a) provides topography, while the BSE image (b) shows differences in composition. Note the compaction of the soil matrix surrounding the vesicle. Scale: Images are 640 micron in width.

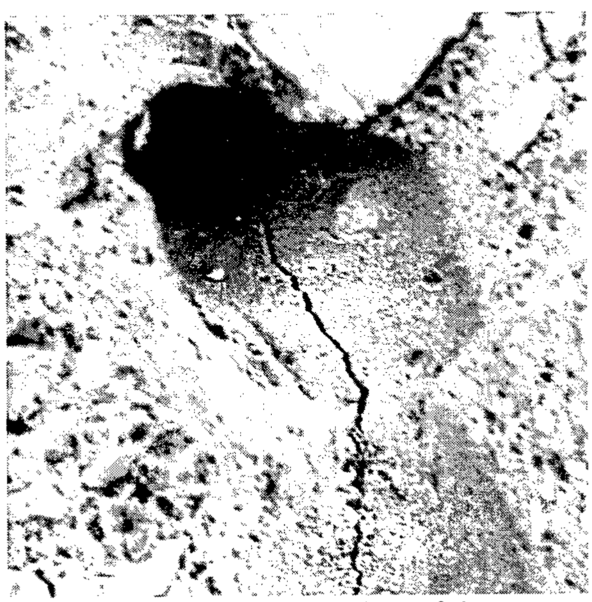


Figure 4-23. This image provides a closer BSE view of the same vesicle showing compaction of the soil plasma more clearly. Water moving through this Av horizon in undisturbed pavement can travel through the vesicle, but is less able to move through the compacted soil plasma. Scale: Image is 242 microns in width.

Microtopography: Track scars average .925 cm below surrounding undisturbed pavement at their lowest point (Appendix D).

Soil Density: Soil is consistently denser under track scarred surfaces than adjacent, undisturbed desert pavement. Troxler gauge readings indicate that soil density averages 1824.56 kg/m^3 (106.96 lb/ft^3) under track scars and 1713.39 kg/m^3 (106.96 lb/ft^3) under undisturbed pavement from 0-20 cm in depth (Figure 4-24).

Discussion

Track Scar Origin and Age

Track scar width and base measurements match M4 Sherman Tanks maneuvering in preparation for World War II. This indicates that the scars in the Butler Pass study site were formed in 1943. Ancillary evidence including date-stamped oil cans and track parts from World War II vintage vehicles found near the study site support this observation. M60 tanks that could have possibly maneuvered in this same area during exercises in 1964 have wider track width and base dimensions, and modern 4x4 wheeled recreation vehicles that are capable of traversing this terrain have much smaller wheel width and base dimensions, suggesting these vehicles are not likely sources of scarring. The track scars under study therefore are approximately 60 years old; yet remain clearly visible today despite decades of desert pavement regeneration.

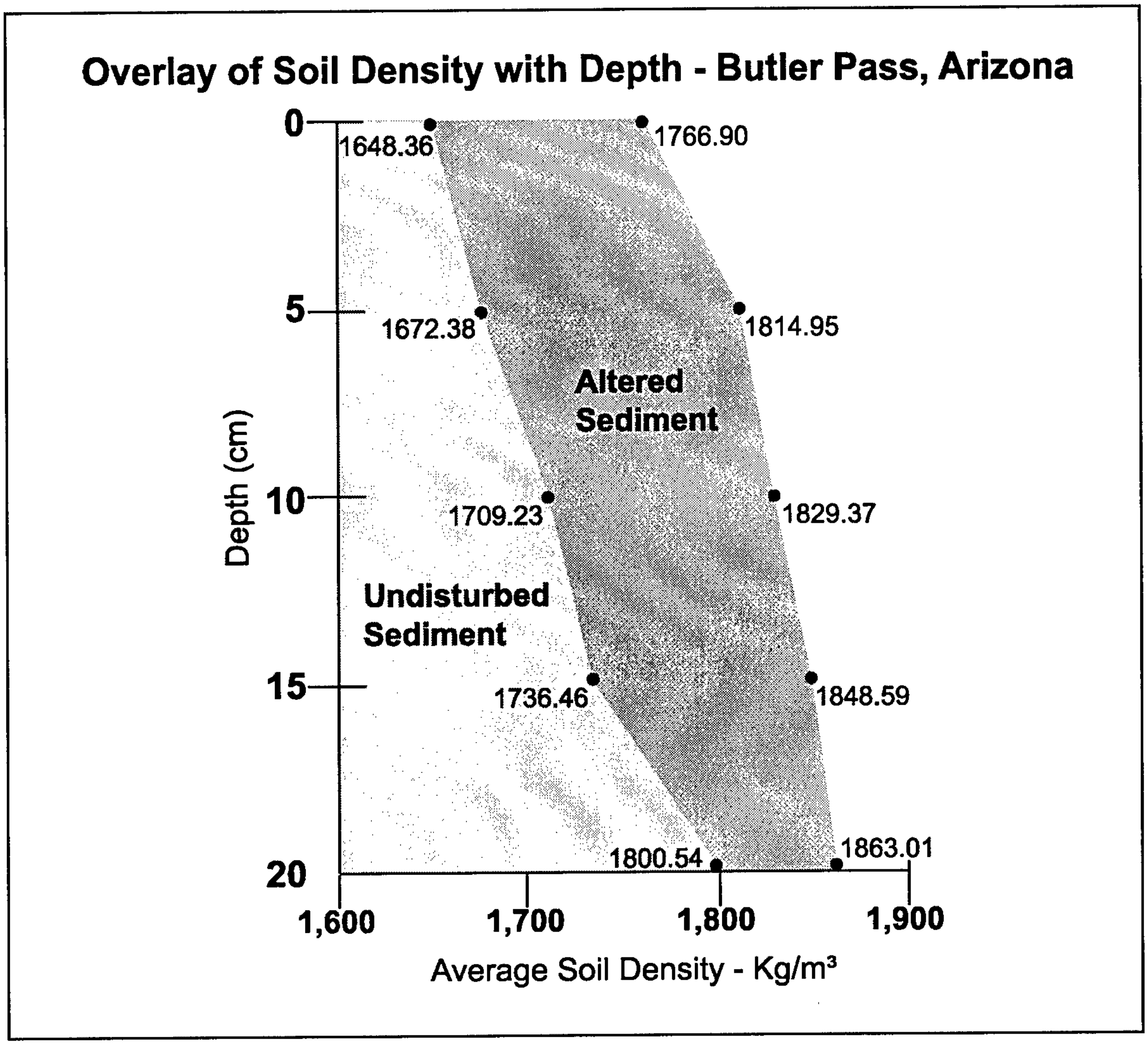


Figure 4-24. Soil density under track scarred pavement averages 111.17 kg/m^3 greater than under undisturbed pavement. This chart shows the difference in soil density with depth.

The Legacy of Track Passage

Reconstruction of conditions and processes before, during, and after track passage requires speculation, but based on evidence uncovered during this investigation, a reconstruction of events provides useful insight. Data analyzed at Butler Pass suggests

that, prior to track maneuver, the small interfluve that makes up the study area consisted of a relatively uniform Av soil horizon approximately 2.3 cm in depth, capped by an indurated desert pavement surface, and underlain by a B horizon heavily interspersed with rocks and rock fragments (Figure 4-25a). The pavement surface was well developed and stable.

Sherman tank maneuvers in 1943/44 crushed and fractured the pavement surface, causing destruction of Av horizon induration and compaction of both the Av and B horizons to an unknown depth (Figure 4-25b). Surface rock particles were driven downward by the weight of the tank. A rut was formed of unknown depth as a result of compaction of the B horizon and compaction and destruction of the Av horizon. The destruction of the indurated surface allowed sediment and other small particles to be relatively more susceptible to movement by surface processes.

Today, approximately 60 years after alteration, the track scars appear as in Figure 4-25c. Track ruts exist and average .925 cm at the deepest point. A partially regenerated Av horizon averaging 3.6 cm in depth has reappeared in these scars, although it is not indurated. Track ruts are capped by a friable layer of granitic, gneissic and quartzite surface particles that are of much smaller size and density than those in undisturbed pavement, but are made up of similar material. Most of these smaller particles are not coated with rock varnish. The boundary between the Av and B horizons in track scars is not clearly defined, but a preponderance of larger rock particles appear in track scars at approximately this depth. The sediment under track scars is more dense than at comparable depths under undisturbed pavement (Appendix F).

A more detailed appraisal of current conditions reveals additional data on regeneration processes occurring at the site (Figure 4-26). Measured differences in micro topography, albedo, rock coatings, surface particle area, volume, density, and mass between scarred and control surfaces suggest the shallow depressions (ruts) left by track passage are being filled with relatively mobile material susceptible to surface geomorphic processes (Table 4-10). Dynamic processes common to desert environments such as wind and surface water flow (sheetflood) can move small particles rapidly (Williams and Zimbelman 1994; Wainwright, Parsons *et al.* 1999) and it is likely that wind and rain events provided the principle regenerative surface processes active during the first decades of desert pavement regeneration. This finding is similar to that expressed by Cooke (1970) and Prose and Wilshire (2000) in their studies on desert pavement.

Surface induration in track scars at Butler Pass is not developed compared to undisturbed pavement. While the strength of this crust is difficult to measure empirically, the friable nature of the scar surface compared to the compact peds of undisturbed pavement is apparent from qualitative observation. The surface of track scars is easily rearranged by finger pressure, whereas the surface of undisturbed pavement is more strongly adherent. The NRCS measure of surface induration (Appendix A) confirms this observation, but more conclusive evidence is available

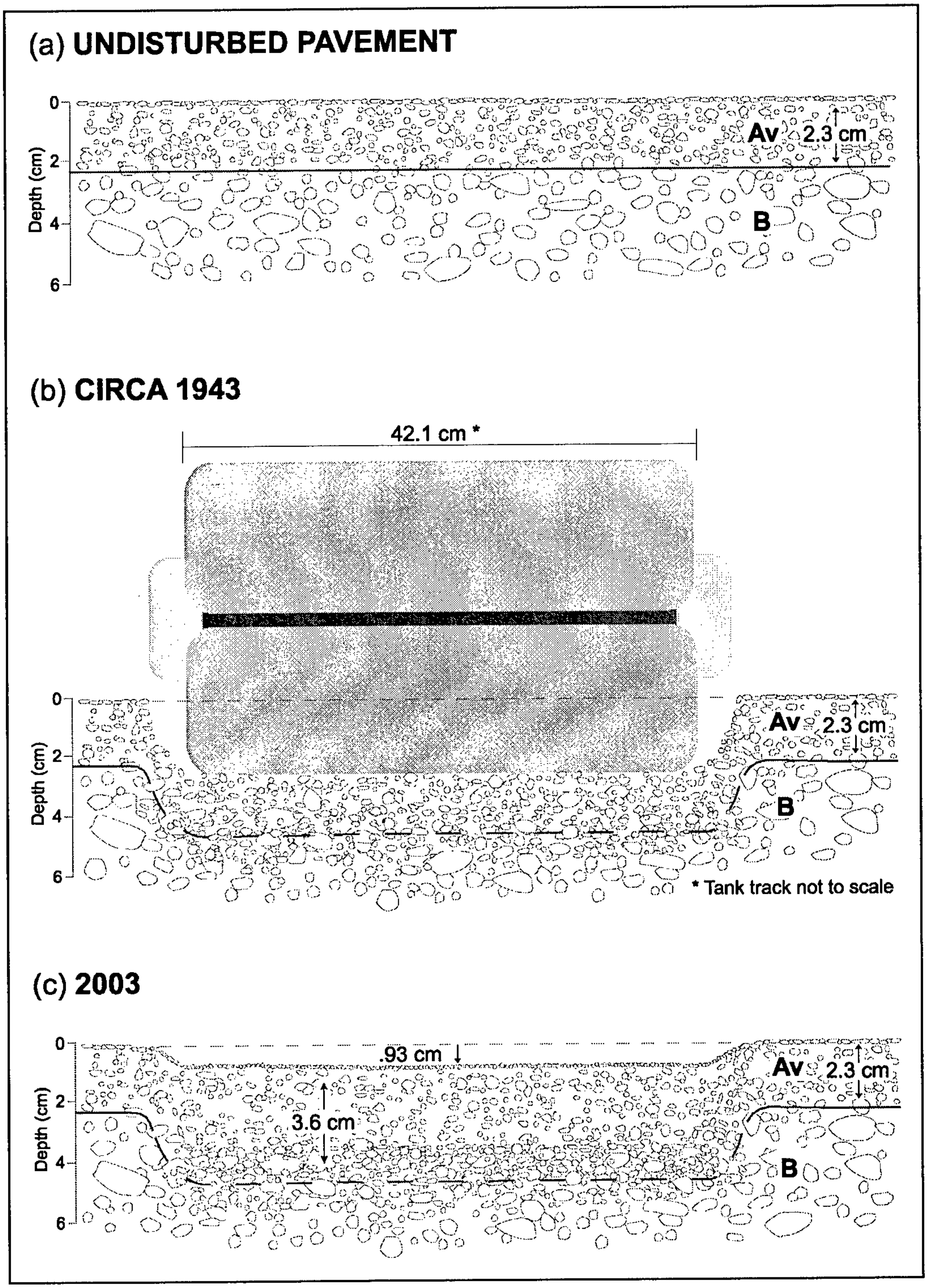


Figure 4-25. An idealized cross-section of desert pavement at Butler Pass. (a) The undisturbed pavement Av horizon averages 2.3 cm in depth. (b) Tank passage destroys surface induration and compacts the sediment. (c) The surface rut is partially filled with small particles as the Av horizon is re-established, but without a surface crust.

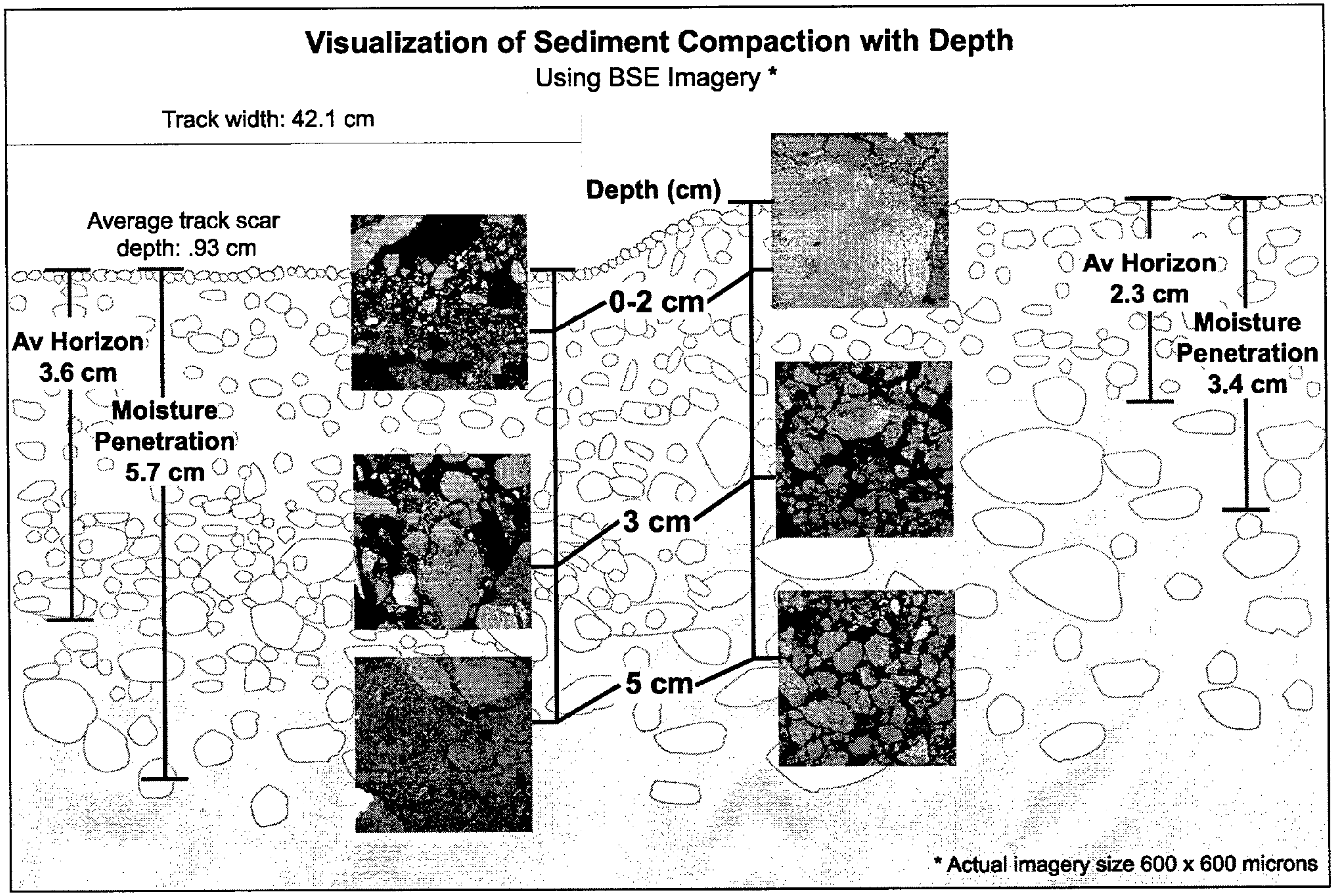


Figure 4-26. Cross-section comparing sediment compaction between undisturbed desert pavement (right) and track scarred pavement (left) using BSE imagery. Undisturbed pavement is more compact near the surface relative to scarred pavement, probably as a result of crustal induration. Track scarred pavement becomes more dense with depth, probably from the weight of the tank as it passed over.

Table 4-10. Summary of surface observations and implications at Butler Pass Study Site.

Category	Implication	In track	Undisturbed Pavement	T-Test Results for Difference of Means Test
Surface Albedo	Higher albedo indicates less rock coatings and thus, higher mobility (scale 0 = black, 255 = white) (Appendix B).	99.4	78.1	significant at α=0.01
Rock Coatings	Lower percentage of rock coatings indicates higher mobility (Appendix C).	86% not coated	74% not coated	significant at α=0.01
Sunlight-Exposed Particle Area	Lower particle surface area suggests higher susceptibility to surface movement (Appendix H).	27.19mm^2	71.6mm^2	significant at α=0.01
Surface Particle Mass	Lower surface particle mass favors surface movement.	36.4 gm	592.4 gm	N/A
Surface Particle Volume	Lower surface particle volume favors surface movement.	30 ml	275 ml	N/A
Surface Particle Density	Lower surface particle density favors surface movement.	12.13 kg/m^3	19.25 kg/m^3	N/A
Surface Particle Sphericity	Higher sphericity favors surface movement (Appendix I).	.5984	.6074	not significant at α=0.05

through BSE imagery. The Av horizon of undisturbed pavement appears strongly compacted with few pore spaces and a tight matrix of solid material in BSE imagery compared to the loosely held fragments in soil under track scars in the first 2 cm of depth.

Subsurface Conditions

The depth of the Av horizon and the vagueness of the Av-B horizon boundary under track scars at Butler Pass still reflect alterations from the passage of heavy tracked vehicles in 1943/44. Measurements of soil density under track scars are consistently greater than under undisturbed pavement, suggesting that the underlying B horizon was compacted from the weight of the passing vehicle and remains so today. Subsequently, the partially regenerated Av horizon under track scars incompletely filled the rut and currently remains thicker relative to undisturbed pavement. The boundary between the Av and B horizon under track scars is not as well developed as under undisturbed pavement because tank passage destroyed the indurated boundary layer, which apparently has not had sufficient time to fully regenerate.

Perhaps the most intriguing observation of this study is the natural moisture penetration depths observed and recreated artificially. Previous literature argues that compaction of soils by tracked vehicle or ORV passage should inhibit moisture penetration (Wilshire and Nakata 1976; Iverson *et al.* 1981; Webb 1983). Evidence at the Butler Pass Study Site indicates otherwise. Observations of moisture penetration into the soil after natural rainfall clearly indicate deeper penetration under track scars than in undisturbed pavement in the first few cm of depth. The conditions were recreated by artificial addition of surface moisture with similar results. This phenomenon is not necessarily contrary to previous research dealing with ORV or other anthropogenic compaction studies, because this study is restricted to desert pavement whereas previous

literature largely dealt with desert soils in general. However, Prose and Wilshire (2000), using a surface infiltrometer, reported up to a 55% lower infiltration rate in desert pavement soils traversed by tanks maneuvering in the same exercises that created the Butler Pass tracks in the early 1940s. BSE imagery of upper soil sediment characteristics at the Butler Pass study site suggests why a reversal of relative moisture penetration depths is evident at this location.

Moisture infiltration is directly related to soil porosity and permeability. Porosity refers to the relative amount of pore space in sediment compared to that occupied by solids. Permeability refers to the capacity of the soil matrix to allow movement of water and is a function of the presence and interconnectedness of these pores. Water in sediment is held by adhesive forces between particles and water molecules, and by the adhesive forces between adjacent water molecules (Birkeland 1999). Water introduced at the surface of dry sediment fills pores spaces, but the outer portion of this water is under low surface tension and is therefore able to move downward in response to gravity (Birkeland 1999). Larger pore spaces allow more water to migrate in this manner.

BSE imagery of sediment samples taken at Butler Pass shows differences with depth in sediment matrix porosity between track scars and undisturbed pavement soils. The upper Av horizon in track scars was probably regenerated primarily from materials brought to the site by wind and surface water action after scar creation, so the Av sediment matrix in these locations is not compacted. The broken soil matrix permits the passage of water. Insufficient time has passed since the destruction of the desert pavement Av horizon by tank maneuvers for significant surface induration to occur. This

is in direct contrast to undisturbed pavement, which displays an indurated, compact soil matrix at the surface. Cooke (1970) proposed that rain drop impact may align the sediment on the surface of arid region soils, and cause them to interlock, forming a crust like that found in undisturbed pavement surfaces at Butler Pass. Overland flow washing fine sediments into near-surface pore spaces may aid this process. Chemical cementation may also have a role in the formation of this crust as well, but the major effect of induration at the surface is the formation of a barrier to moisture infiltration that is characteristic of undisturbed desert pavement, but not present in track scars at this study site. Regardless of the permeability and porosity at lower depths, these surface characteristics of undisturbed pavement cause a great deal of surface water to run off to other locations and not be able to penetrate to lower depths.

At the 3 cm depth, BSE imagery reveals similar circumstances regarding soil matrix compaction. The Av horizon in undisturbed sediment appears slightly more compacted than that of track scarred sediments. The difference, however, is less sharp here indicating a lower capacity for downward movement of moisture in response to gravity. At the 5 cm depth, soil compaction under track scars is clearly visible, while the soil matrix under undisturbed pavement is relatively loosely packed. Moisture infiltration under the influence of gravity would likely be favored in undisturbed pavement at this depth.

Water infiltration, therefore, in the first 2 cm of the Av horizon, is relatively rapid in track scars where the indurated crust has been destroyed and has not yet reformed. At the 3 cm depth, a reversal of soil matrix compaction begins to appear, where undisturbed

pavement sediment is much less compact than at the 2 cm depth, and sediment under track scars appears slightly more compact than at the 2 cm depth. Should moisture infiltrate to this depth, it would probably be able to move rapidly through both scarred and undisturbed pavement. At the 5 cm depth, the sediment under track scars is clearly compacted, probably because of the weight of track passage. Sediment in undisturbed pavement is more broken with more pore space apparent. Moisture at this depth could move more easily through undisturbed sediment than through sediment under track scars.

The observed moisture infiltration depths at the Butler Pass Study Site are consistently deeper under track scars than under undisturbed pavement. This suggests that the indurated surface of undisturbed pavement inhibits moisture infiltration at the surface. Less moisture penetrates the Av horizon to depths where the sediment is relatively more permeable and porous. In tank tracks, surface induration is less well developed and moisture is more readily absorbed at the surface, allowing a comparatively larger volume of moisture to be introduced to lower depths over the same amount of time compared to adjacent, undisturbed pavement.

The implication of more rapid moisture infiltration in the upper soil profile under track scars at Butler Pass is important because the addition of moisture is essential to at least one theory of surface particle concentration on desert pavements. Cycles of sediment wetting and desiccation support the theory of upward migration of particles (Springer 1958; Jessup 1960). The unexpected and relatively more rapid infiltration characteristics of track scarred sediment compared to undisturbed sediment suggests that

this process may be significant to the long term regeneration of desert pavement at Butler Pass.

Observed moisture penetration at the study site is restricted to the upper 6 cm of soil depth. A key factor inhibiting the upward migration of large clasts in track scars at lower depths is soil compaction caused by the weight of the passing tank. Soil density increases approximately 1602 kg/m^3 (100 lbs/ft^3) from 5 to 10 cm in depth in track scarred pavement. Therefore, deeper moisture penetration is indeed limited in this location as Cooke (1970) and Prose and Wilshire (2000) and others predict. Thus, at Butler Pass, pavement regeneration by the process of upward particle migration may be occurring at a relatively rapid rate in the upper soil profile, but is progressively more retarded as soil compaction with depth outweighs the advantage gained by the destruction and continued absence of surface induration. Regardless, 60 years has not been sufficient time to allow this process to regenerate a surface layer of clasts similar in size to those in undisturbed pavement.

Conclusion

Dynamic geomorphic processes common to desert environments have reworked pavement surfaces at Butler Pass, yet regeneration is not complete. Assuming the regeneration endstate would make track scars and underlying pavement soil undifferentiated from undisturbed pavement, the time and conditions required for this change are significant. Continued regeneration requires movement of larger clasts onto scarred surfaces, and this takes long periods of time to accomplish. Introduction of larger clasts to the surface of track scars can be accomplished through the upward migration of particles (Springer 1958; Jessup 1960; Cooke 1970), thermogenic (McFadden *et al.* 1987; McFadden 2001) or salt (Amit *et al.* 1993) rock shattering, or large-clast surface movement into the topographic micro-depressions of the scarred surface. Each of these processes may have been occurring at a slow rate at Butler Pass since scar generation in the early 1940s, but few clasts with a "sunlight-exposed" surface area larger than 30 mm^2 exist in track scars currently.

Because of the affinity of the upper-scarred Av horizon soil to allow water infiltration, data from this study suggest that upward migration of surface particles may be a significant ongoing process. Jessup (1960) caused particles suspended in 'stony tableland soils' to move 2.2 cm in 22 solution/desiccation cycles. If the capacity for moisture to infiltrate track scarred sediment at Butler Pass is greater than that of undisturbed sediment, then the rate of upward migration should be greater in these areas, at least to the depth of repetitive moisture penetration. Below this depth, soil at Butler

Pass is more compacted, and sediment permeability and porosity is probably less than that of adjacent undisturbed pavement.

Results of this study suggest that damage caused by tank maneuvers on desert pavement at Butler Pass is slowly changing, initially by surface processes that likely include overland flow and aeolian forces generating a thick Av horizon and in-filling of the ruts with small surface particles. Further, the unexpected observation of deeper moisture infiltration depths under track scarred pavement suggests that these areas may support some regeneration processes acting more rapidly than under the indurated, undisturbed pavement. The moisture infiltration depths under track scars are most likely the result of the absence of an indurated surface layer that blocks the initial infiltration of moisture, and the presence of microtopographic lows in the track scar surface that may encourage pooling of moisture. The lack of a sharply delineated and indurated upper plane of the B horizon compared to undisturbed areas may also serve to encourage moisture penetration.

Desert pavement is ubiquitous in arid regions, occurring with regularity on weathered debris mantles, alluvial fans and soils worldwide (Cooke, 1993). Human encroachment on this landform type will continue in the future and military operations are certain to alter these surfaces in regions where arid zone training takes place (such as the arid southwestern United States), or where combat operations may occur in other parts of the world. While damage to desert pavement from maneuvers is an environmental hazard of military necessity, these activities also provide an opportunity for long-term research that may not otherwise be possible. As demonstrated in this study,

deduction of the vehicle type that created landscape alteration indicates the time of alteration with accuracy, and further analysis can be attempted with knowledge of vehicle characteristics such as weight, ground pressure, track surface characteristics and others. Further study concerning the track scars at Butler Pass should investigate soil compaction in detail and its effect on regenerative processes, especially that of upward particle migration. Further research should also investigate the effect surface induration has on the capacity of regenerative processes to be effective at this site.

The linkage between geomorphology and military operations that this study investigates is largely a bi-directional relationship. The dynamic nature of the physical landscape has great influence on the conduct of war, and the actions humans take during conflict and training have the potential to alter landscape processes, rates, and morphology. Alteration of the landscape is an unavoidable consequence of military training and wartime operations, but these activities can create unique opportunities for research.

CHAPTER V: DISSERTATION SUMMARY AND CONCLUSIONS

The purpose of this research is to investigate linkages between the science of geomorphology and the conduct of military operations. While soldiers tend to see the environment in applied terms, geomorphologists view the physical landscape and the processes at work on it from both applied and theoretical perspectives. Both of these views are necessary to gain knowledge and understanding of the complex world in which we live, and to assist in solving real-world problems.

This research presents both the soldiers' and the geomorphologists' views of the desert environment. Chapter II investigates the perception of geomorphic homogeneity in the desert, a view that has proven problematic for armed forces throughout history. Even today for example, the United States Army classifies deserts simply and disingenuously. Despite the natural variability in environmental conditions that produce a great variety of desert types, the Army regulation that governs research, development, testing, and evaluation (RDT&E) defines desert temperature extremes simplistically as cold (to -35 $^{\circ}$F) and hot (to 120 $^{\circ}$F) (United States Army Regulation 70-38 1979). Professional academics outside the military are challenged by the diversity and complexity of desert environments. Areas in conflict or closed by political regimes make on-the-ground research undesirable or dangerous, limiting the ability to conduct thorough research. The result can be misconception of the complexity of the environment, and perhaps an underestimation of geomorphic variety and its effects. The research in this dissertation demonstrates that even in the very accessible and well-known local desert areas of the southwestern United States, there is a tendency to oversimplify and perhaps

underestimate surface complexity. These issues should be known and accounted for in research. They may have tremendous repercussions in war.

In 2003, the United States Army commissioned a Desert Natural Environment Peer Panel to expand understanding of how to characterize desert regions in support of RDT&E (King 2003). The mission of this group is, in part, to develop a model that characterizes deserts and arid environments by a set of scientific parameters, and to apply this desert characterization model to the world's deserts to differentiate sub-categories that are significant from a military standpoint for testing and evaluation of equipment (King 2003). This project has similarities with Chapter III of this dissertation. It is the result of a recognition that a gap in knowledge of non-temperate operating environments exists, and it establishes a conceptual framework to help fill that gap. The purpose of the model presented in this dissertation is a response to a perceived gap in knowledge and understanding of non-temperate military operating environments. It is designed to offer a widely available method to help soldiers and others understand the complexity of desert environments and the general effects they have on military operations. Clearly, justification of the pursuit of such models exist, particularly given the Army's funding of over $90,000 in support of this most recent project (King 2003), and the pursuit of a previous project concerning the tropical environment that was undertaken in 1998 (King, Harmon et al. 1998).

A hazard associated with all military operations is damage to the environment. While the United States Army takes great pains to minimize and mitigate this damage, it will continue to occur as long as this nation ranks its geopolitical will and the importance

of its soldier's lives above the immediate environmental costs that may result from their actions. Chapter IV of this dissertation investigates one facet of the effects that military maneuvers have on deserts. This investigation reveals that while desert pavement in the study area was greatly altered by tank maneuvers, track scarred areas support moisture penetration into the subsurface, which enhances and is a necessary condition for vegetative growth or re-growth. Furthermore, the conditions surrounding the cause of the pavement alteration are traceable, allowing researchers a rare opportunity to conduct investigations on relatively long-term geomorphic processes. Contrary to the widely accepted perception that all tank maneuvers on fragile arid landscapes are degenerative, this study points out that there are positive aspects that can result from military maneuver.

The linkages between the science of geomorphology and military operations are vast and may be considered bi-directional. Physical environmental conditions and processes greatly affect the conduct of military operations, and military operations invariably have a tremendous effect on the physical environment. The role of geomorphology in investigating these linkages is clear. This dissertation explores a small segment of this wide and fertile area of study and is an appropriate and timely investigation given the resurgence in demand and popularity of this subfield of military geography.

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APPENDIX A

FIELD SOIL DESCRIPTIONS

Field Soil Description
Site Number 1 BORON

Date: 7 June 2001
Location: 35 Degrees, 03.789 Minutes North, 117 Degrees, 42.906 Minutes West, UTM 11S MJ 3479680279
Slope: None
Sampling Method: Backhoe

Time: 1037
Elevation: 2490 Feet

Aspect: Azimuth 350, trench length 27 feet

Depth	Horizon	Color (Dry)	Color (Wet)	Structure	% Gravel	Consistency	Texture	Remarks
3 Inches	Av	7.5 YR 5/4	7.5 YR 4/6	Granular	10 %	Friable	Loamy Sand	No effervescence, some grass roots
24 Inches	Bw1	7.5 YR 4/6	7.5 YR 4/4	SBK	5%	Friable	Sandy Loam	No effervescence
48 Inches	Bw2	5 YR 4/6	5 YR 4/3	SBK	2%	Firm	Loam	No effervescence

General Comments:
Appears to be the sand sheet, probably mobilized and deposited 6-8 KBP in the Holocene.

Field Soil Description
Site Number 2 BORON

Date: 7 June 2001
Location: 35 Degrees, 03.680 Minutes North, 117 Degrees, 42.838 Minutes West, UTM 11S MJ 3489780077
Slope: None
Sampling Method: Backhoe

Time: 1212
Elevation: 2462 Feet

Aspect: Azimuth 335, trench length 75 feet

Depth	Horizon	Color (Dry)	Color (Wet)	Structure	% Gravel	Consistency	Texture	Remarks
4 Inches	Av	7.5 YR 6/3	7.5 YR 4/3	Grainy Platy	10 %	Firm	Clay Loam	Light effervescence
25 Inches	AB	7.5 YR 5/8	5 YR 4/4	SBK	3%	Slightly Sticky, Slightly Plastic	Sandy Loam	No effervescence
48 Inches +	Bw	5 YR 5/6	5 YR 5/4	ABK	40%	Stickly, plastic	Sandy Clay Loam	No effervescence

General Comments:

Late Holocene Sand Ramp.
Represents pulse near igneous ridge, but ferrous rocks appear on top of and in the sand. Therefore, it appears that this was formed during a pulse of dry weather 6-8 KBP. Fluvial gravels on the bottom indicate low energy deposition. Probably occurred in the Late Pliestocene.

Field Soil Description
Site Number 3 BORON

Date: 7 June 2001
Location: 35 Degrees, 03.817 Minutes North, 117 Degrees, 43.035 Minutes West, UTM 11S MJ 3460080352
Slope: None
Sampling Method: Backhoe

Elevation: 738 meters

Aspect: Azimuth 320, trench length 28 feet

Depth	Horizon	Color (Dry)	Color (Wet)	Structure	% Gravel	Consistency	Texture	Remarks
1 Inch	Av	7.5 YR 6/4	7.5 YR 5/4	Platy	10 %	Sticky, Plastic	Sandy Loam	No effervescence
24 Inches	Bw	5 YR 4/4	5 YR 4/3	ABK	2%	Sticky, Plastic	Sandy Clay Loam	Moderate effervescence
36 Inches	Bt1	5 YR 4/4	5 YR 4/3	ABK	< 2%	Sticky, plastic	Clay Loam	Strong effervescence
48 Inches +	Bt2	5 YR 4/6	5 YR 4/4	Columnal	<2%	Sticky, plastic	Sandy Clay Loam	Violent (Stage II +)

General Comments:
Appears to be a pliestocene paleosol with aeolian cover.
Discovered a carbon layer in the Bt2 horizon. The nodular CaCO3 is a Holocene imprint. Sending the carbon in for 14C dating. Hypothesize 11,500 to 15 or 16kBP dating.

Field Soil Description
Site Number 4 BORON

Date: 7 June 2001
Location: 35 Degrees, 03.720 Minutes North, 117 Degrees, 42.566 Minutes West, UTM 11S MJ 3531180148
Slope: None
Sampling Method: Backhoe

Time: 1610
Elevation: 2469 Feet

Aspect: Azimuth 287, trench length 45 feet

Depth	Horizon	Color (Dry)	Color (Wet)	Structure	% Gravel	Consistency	Texture	Remarks
4 Inches	Av	5 YR 6/4	5 YR 5/3	Grainy, somewhat Platy	1 %	Friable	Loamy Sand	Light effervescence
38 Inches	AB/Bw	5 YR 5/6	5 YR 4/6	SBK	< 5%	Friable	Sandy Loam	No effervescence
48 Inches +	Bw	5 YR 5/6	5 YR 4/4	ABK	<3%	Friable	Sandy Loam	Light effervescence

General Comments:
Probably end of Pleistocene/Early Holocene soil. Similar attributes to Trench 6, but less induration. More Quartz sand and less clay appear here than in trench 6.

Field Soil Description
Site Number 5 (North of Edwards AFB)

Date: 8 June 2001
Time: 0840
Location: 35 Degrees, 00.926 Minutes North, 117 Degrees, 35.023 Minutes West, UTM 11S MJ 4674574909
Elevation: 2398 Feet
Slope: None
Aspect: NA
Sampling Method: Backhoe (old sump trench)

Depth	Horizon	Color (Dry)	Color (Wet)	Structure	% Gravel	Consistency	Texture	Remarks
1 Inch	A1	7.5 YR 5/4	7.5 YR 4/4	Granular	12 %	Friable	Loamy Sand	No effervescence
6 Inches	A2 or AB	7.5 6/4	7.5 4/4	SBK Weak	3 %	Slightly Sticky, Slightly plastic	Sandy Loam	No effervescence
25 Inches	Bw	7.5 YR 5/6	7.5 YR 4/6	SBK Weak	3%	Slightly Sticky, Slightly plastic	Sandy Loam	No effervescence
36 Inches +	Bk	5 YR 5/8	5 YR 4/6	SBK	3%	Slightly Sticky, Slightly plastic	Sandy Loam	Strong effervescence Stage I

Field Soil Description
Site Number 6 (Drainage Ditch at Boron - dated)

Date: 8 June 2001
Location: 35 Degrees, 03.742 Minutes North, 117 Degrees, 43.136 Minutes West, UTM 11S MJ 3444580194
Slope: None

Time: 1033
Elevation: 2500 Feet (753 m)

Sampling Method: Drainage Ditch

Depth	Horizon	Color (Dry)	Color (Wet)	Structure	% Gravel	Consistency	Texture	Remarks
12 Inches	AV	7.5 YR 6/4	7.5 YR 4/4	Platy on top, then sbk	15 %	Sticky/Plastic	Loam	No effervescence
48 Inches	BW1	5 YR 5/6	5 YR 4/6	SBK	10 %	Sticky/Plastic	Silty clay loam	Strong effervescence
72 Inches	BK1	7.5 YR 8/2	7.5 YR 7/3	ABK	40 % (calcrete)	Slightly Sticky, Slightly plastic	Clay Loam (velvety)	Stage II
84 Inches	Bk2	5 YR 7/3	5 YR 7/4	Platy	25% (Calcrete)	Slightly Sticky, Slightly plastic	Sandy Loam	Stage II
92 Inches +	2BK	7.5 YR 8/3	7.5 YR 5/6	Platy	35 %	Not Sticky, Not plastic	Sandy Loam	Stage III

General Comments:
Already have a 14C date from the Bk2 layer of 25-30KBP. Lots of clay and coherent peds appear in this profile.

Field Soil Descriptions (a)

Sample: 231203 JAN 03 Av OUT **Location:** BUTLER PASS

Slope: .5° **Elevation:** 520M

Track Scar or Undisturbed Pavement

Depth (cm)	Horizon	Horizon Boundary	Color Moist / Dry	Structure	% Gravel	Consistence Dry	Consistence Moist	Consistence Wet (& plasticity)	Texture (b)	Surface Crust and Plates	Carbonate Effer-vescence
2.4	Av	VA A s C w G l D b	7.5yr 5/4 ——— 7.5yr 4/4	Grade Class Type m vf gr sg f pl 1 m pr 2 c cpr 3 vc abk sbk	0 <10 10-24 25-50 50-75 >75	Lo So Sh H Vh Eh	Lo Vfr Fr Fi Vfi Efi	so po ss ps s p vs vp	S SiCl LS SiL SL Si SCL SiC L C CL SC	EW VW W M MS S VS ES	Very Slight Slight Strong Violent
2.4 ↓	B	VA A s C w G l D b	5yr 5/6 ——— 5yr 4/6	Grade Class Type m vf gr sg f pl 1 m pr 2 c cpr 3 vc abk sbk	0 <10 10-24 25-50 50-75 >75	Lo So Sh H Vh Eh	Lo Vfr Fr Fi Vfi Efi	so po ss ps s p vs vp	S SiCl LS SiL SL Si SCL SiC L C CL SC	EW VW W M MS S VS ES	Very Slight Slight Strong Violent

Note: (a) All data categories and test criteria are from Birkeland (1999) and Schoeneberger *et al.*, (1998) (b) Test completed without access to calibration sample.

Field Soil Descriptions (a)

Sample: 231203 JAN 03 AIN **Location:** BUTLER PASS

Slope: .5° **Elevation:** 520m

Track Scar or Undisturbed Pavement

Depth (cm)	Horizon	Horizon Boundary	Color Moist / Dry	Structure	% Gravel	Consistence Dry	Consistence Moist	Consistence Wet (& plasticity)	Texture (b)	Surface Crust and Plates	Carbonate Effer-vescence
3.0	Av	VA A s C w G l D b	7.5yr 5/4 ——— 7.5yr 4/3	Grade Class Type m vf gr sg f pl 1 m pr 2 c cpr 3 vc abk sbk	0 <10 10-24 25-50 50-75 >75	Lo So Sh H Vh Eh	Lo Vfr Fr Fi Vfi Efi	so po ss ps s p vs vp	S SiCl LS SiL SL Si SCL SiC L C CL SC	EW VW W M MS S VS ES	Very Slight Slight Strong Violent
3.0 ↓	B	VA A s C w G l D b	5yr 5/6 ——— 5yr 4/6	Grade Class Type m vf gr sg f pl 1 m pr 2 c cpr 3 vc abk sbk	0 <10 10-24 25-50 50-75 >75	Lo So Sh H Vh Eh	Lo Vfr Fr Fi Vfi Efi	so po ss ps s p vs vp	S SiCl LS SiL SL Si SCL SiC L C CL SC	EW VW W M MS S VS ES	Very Slight Slight Strong Violent

Note: (a) All data categories and test criteria are from Birkeland (1999) and Schoeneberger *et al.*, (1998) (b) Test completed without access to calibration sample.

Field Soil Descriptions (a)

Sample: Z31446 JAN 03 COUT **Location:** BUTLER PASS

Slope: 0° **Elevation:** 520 m

Track Scar or Undisturbed Pavement

Depth (cm)	Horizon	Horizon Boundary	Color Moist / Dry	Structure	% Gravel	Consistence Dry	Consistence Moist	Consistence Wet (& plasticity)	Texture (b)	Surface Crust and Plates	Carbonate Effervescence
22	Av	VA A s C w G l D b	7.5yr 4/4 7.5 6/4	Grade Class Type m vf gr sg f pl 1 m pr 2 c cpr 3 vc abk sbk	0 <10 10-24 25-50 50-75 >75	Lo So Sh H Vh Eh	Lo Vfr Fr Fi Vfi Efi	so po ss ps s p vs vp	S SiCl LS SiL SL Si SCL SiC L C CL SC	EW VW W M MS S VS ES	Very Slight Slight Strong Violent
2.2 ↓	B	VA A s C w G l D b	5yr 4/4 5yr 4/6	Grade Class Type m vf gr sg f pl 1 m pr 2 c cpr 3 vc abk sbk	0 <10 10-24 25-50 50-75 >75	Lo So Sh H Vh Eh	Lo Vfr Fr Fi Vfi Efi	so po ss ps s p vs vp	S SiCl LS SiL SL Si SCL SiC L C CL SC	EW VW W M MS S VS ES	Very Slight Slight Strong Violent

Note: (a) All data categories and test criteria are from Birkeland (1999) and Schoeneberger *et al.*, (1998) (b) Test completed without access to calibration sample.

Field Soil Descriptions (a)

Sample: Z31446 JAN 03 CIN **Location:** BUTLER PASS

Slope: 0° **Elevation:** 520 m

Track Scar or Undisturbed Pavement

Depth (cm)	Horizon	Horizon Boundary	Color Moist / Dry	Structure	% Gravel	Consistence Dry	Consistence Moist	Consistence Wet (& plasticity)	Texture (b)	Surface Crust and Plates	Carbonate Effervescence
2.4	Av	VA A s C w G l D b	7yr 4/4 7yr 6/4	Grade Class Type m vf gr sg f pl 1 m pr 2 c cpr 3 vc abk sbk	0 <10 10-24 25-50 50-75 >75	Lo So Sh H Vh Eh	Lo Vfr Fr Fi Vfi Efi	so po ss ps s p vs vp	S SiCl LS SiL SL Si SCL SiC L C CL SC	EW VW W M MS S VS ES	Very Slight Slight Strong Violent
2.4 ↓	B	VA A s C w G l D b	5yr 4/4 5yr 5/8	Grade Class Type m vf gr sg f pl 1 m pr 2 c cpr 3 vc abk sbk	0 <10 10-24 25-50 50-75 >75	Lo So Sh H Vh Eh	Lo Vfr Fr Fi Vfi Efi	so po ss ps s p vs vp	S SiCl LS SiL SL Si SCL SiC L C CL SC	EW VW W M MS S VS ES	Very Slight Slight Strong Violent

Note: (a) All data categories and test criteria are from Birkeland (1999) and Schoeneberger *et al.*, (1998) (b) Test completed without access to calibration sample.

Field Soil Descriptions (a)

Sample: 231320 JAN 03 BOUT **Location:** BUTLER PASS

Slope: .5° **Elevation:** 520 M

Track Scar or Undisturbed Pavement

Depth (cm)	Horizon	Horizon Boundary	Color Moist / Dry	Structure	% Gravel	Consistence Dry	Consistence Moist	Consistence Wet (& plasticity)	Texture (b)	Surface Crust and Plates	Carbonate Effer-vescence
1.8	Av	VA A s C w G l D b	7.5yr 4/4 7.5yr 5/6	Grade Class Type m vf gr sg f pl 1 m pr 2 c cpr 3 vc abk sbk	0 <10 10-24 25-50 50-75 >75	Lo So Sh H Vh Eh	Lo Vfr Fr Fi Vfi Efi	so po ss ps s p vs vp	S SiCl LS SiL SL Si SCL SiC L C CL SC	EW VW W M MS S VS ES	Very Slight Slight Strong Violent
1.8 ↓	B	VA A s C w G l D b	5yr 4/4 5yr 4/6	Grade Class Type m vf gr sg f pl 1 m pr 2 c cpr 3 vc abk sbk	0 <10 10-24 25-50 50-75 >75	Lo So Sh H Vh Eh	Lo Vfr Fr Fi Vfi Efi	so po ss ps s p vs vp	S SiCl LS SiL SL Si SCL SiC L C CL SC	EW VW W M MS S VS ES	Very Slight Slight Strong Violent

Note: (a) All data categories and test criteria are from Birkeland (1999) and Schoeneberger *et al.*, (1998) (b) Test completed without access to calibration sample.

Field Soil Descriptions (a)

Sample: 231320 JAN 03 BIN **Location:** BUTLER PASS

Slope: .5° **Elevation:** 520 M

Track Scar or Undisturbed Pavement

Depth (cm)	Horizon	Horizon Boundary	Color Moist / Dry	Structure	% Gravel	Consistence Dry	Consistence Moist	Consistence Wet (& plasticity)	Texture (b)	Surface Crust and Plates	Carbonate Effer-vescence
2.6	Av	VA A s C w G l D b	7yr 4/4 7yr 5/6	Grade Class Type m vf gr sg f pl 1 m pr 2 c cpr 3 vc abk sbk	0 <10 10-24 25-50 50-75 >75	Lo So Sh H Vh Eh	Lo Vfr Fr Fi Vfi Efi	so po ss ps s p vs vp	S SiCl LS SiL SL Si SCL SiC L C CL SC	EW VW W M MS S VS ES	Very Slight Slight Strong Violent
2.6 ↓	B	VA A s C w G l D b	5yr 4/4 5yr 4/6	Grade Class Type m vf gr sg f pl 1 m pr 2 c cpr 3 vc abk sbk	0 <10 10-24 25-50 50-75 >75	Lo So Sh H Vh Eh	Lo Vfr Fr Fi Vfi Efi	so po ss ps s p vs vp	S SiCl LS SiL SL Si SCL SiC L C CL SC	EW VW W M MS S VS ES	Very Slight Slight Strong Violent

Note: (a) All data categories and test criteria are from Birkeland (1999) and Schoeneberger *et al.*, (1998) (b) Test completed without access to calibration sample.

Field Soil Descriptions (a)

Sample: 231500 JAN 03 DOUT **Location:** BUTLER PASS
Slope: .5° **Elevation:** 520 M

Track Scar or Undisturbed Pavement

Depth (cm)	Horizon	Horizon Boundary	Color Moist / Dry	Structure	% Gravel	Consistence Dry	Consistence Moist	Consistence Wet (& plasticity)	Texture (b)	Surface Crust and Plates	Carbonate Effer-vescence
1.5	Av	VA A s C w G I D b	7.5yr 4/4 7.5yr 6/3	Grade Class Type m vf gr sg f pl 1 m pr 2 c cpr 3 vc abk sbk	0 <10 10-24 25-50 50-75 >75	Lo So Sh H Vh Eh	Lo Vfr Fr Fi Vfi Efi	so po ss ps s p vs vp	S SiCl LS SiL SL Si SCL SiC L C CL SC	EW VW W M MS S VS ES	Very Slight Slight Strong Violent
1.5 ↓	B	VA A s C w G I D b	5yr 4/4 5yr 5/6	Grade Class Type m vf gr sg f pl 1 m pr 2 c cpr 3 vc abk sbk	0 <10 10-24 25-50 50-75 >75	Lo So Sh H Vh Eh	Lo Vfr Fr Fi Vfi Efi	so po ss ps s p vs vp	S SiCl LS SiL SL Si SCL SiC L C CL SC	EW VW W M MS S VS ES	Very Slight Slight Strong Violent

Note: (a) All data categories and test criteria are from Birkeland (1999) and Schoeneberger *et al.*, (1998) (b) Test completed without access to calibration sample.

Field Soil Descriptions (a)

Sample: 231500 JAN 03 DIN **Location:** BUTLER PASS
Slope: .5° **Elevation:** 520 M

Track Scar or Undisturbed Pavement

Depth (cm)	Horizon	Horizon Boundary	Color Moist / Dry	Structure	% Gravel	Consistence Dry	Consistence Moist	Consistence Wet (& plasticity)	Texture (b)	Surface Crust and Plates	Carbonate Effer-vescence
2.4	Av	VA A s C w G I D b	7.5yr 4/4 7.5yr 6/4	Grade Class Type m vf gr sg f pl 1 m pr 2 c cpr 3 vc abk sbk	0 <10 10-24 25-50 50-75 >75	Lo So Sh H Vh Eh	Lo Vfr Fr Fi Vfi Efi	so po ss ps s p vs vp	S SiCl LS SiL SL Si SCL SiC L C CL SC	EW VW W M MS S VS ES	Very Slight Slight Strong Violent
2.4 ↓	B	VA A s C w G I D b	—	Grade Class Type m vf gr sg f pl 1 m pr 2 c cpr 3 vc abk sbk	0 <10 10-24 25-50 50-75 >75	Lo So Sh H Vh Eh	Lo Vfr Fr Fi Vfi Efi	so po ss ps s p vs vp	S SiCl LS SiL SL Si SCL SiC L C CL SC	EW VW W M MS S VS ES	Very Slight Slight Strong Violent

Note: (a) All data categories and test criteria are from Birkeland (1999) and Schoeneberger *et al.*, (1998) (b) Test completed without access to calibration sample.

APPENDIX B

ALBEDO

Table B-1. Albedo mean, standard deviation, and median values for digital imagery of track scar surface (in) and undisturbed pavement surface (out). Albedo is measured on a scale of 0-255 with black = 0 and white = 255.

Image	In	Out	Albedo Mean	Albedo Standard Deviation	Albedo Median
P1010003_OUT_Crop_Level		X	92.48	88.78	69
P1010004_IN_Crop_Level	X		101.53	86.34	95
P1010005_OUT_Crop_Level		X	94.16	88.01	86
P1010006_IN_Crop_Level	X		102.48	84.61	97
P1010007_OUT_Crop_Level		X	76.25	84.75	37
P1010008_IN_Crop_Level	X		106.17	88.91	97
P1010009_OUT_Crop_Level		X	80.61	85.32	49
P1010010_IN_Crop_Level	X		102.26	85.06	95
P1010011_OUT_Crop_Level		X	78.02	87.68	33
P1010012_IN_Crop_Level	X		96.72	84.55	80
P1010013_OUT_Crop_Level		X	87.86	88.56	59
P1010014_IN_Crop_Level	X		96.45	81.41	85
P1010015_OUT_Crop_Level		X	73.34	84.56	36
P1010016_IN_Crop_Level	X		91.85	82.94	75
P1010017_OUT_Crop_Level		X	69.42	77.32	46
P1010018_IN_Crop_Level	X		100.32	83.43	95
P1010019_OUT_Crop_Level		X	75.8	77.95	57
P1010020_IN_Crop_Level	X		101.89	84.66	101
P1010021_OUT_Crop_Level		X	66.75	79.82	33
P1010022_IN_Crop_Level	X		108.39	87.03	109
P1010023_OUT_Crop_Level		X	78.14	81.63	55
P1010024_IN_Crop_Level	X		89.84	81.02	78
P1010025_OUT_Crop_Level		X	67.67	81.46	31
P1010026_IN_Crop_Level	X		105.74	84.75	106
P1010027_OUT_Crop_Level		X	78.48	83.70	50
P1010028_IN_Crop_Level	X		98.81	84.91	90
P1010029_OUT_Crop_Level		X	70.96	78.86	42
P1010030_IN_Crop_Level	X		81.02	82.67	56
P1010031_OUT_Crop_Level		X	63.84	80.77	26
P1010032_IN_Crop_Level	X		84.80	83.06	66
P1010033_OUT_Crop_Level		X	61.32	78.22	22
P1010034_IN_Crop_Level	X		79.56	83.62	51

Table B-1 (continued)

Image	In	Out	Albedo Mean	Albedo Standard Deviation	Albedo Median
P1010035_OUT_Crop_Level		X	56.67	80.67	8
P1010036_IN_Crop_Level	X		83.34	85.67	57
P1010037_OUT_Crop_Level		X	89.9	73.72	86
P1010038_IN_Crop_Level	X		104.77	85.47	101
P1010039_OUT_Crop_Level		X	95.61	85.36	87
P1010040_IN_Crop_Level	X		99.56	88.07	87
P1010041_OUT_Crop_Level		X	72.65	83.36	39
P1010042_IN_Crop_Level	X		103.78	85.31	97
P1010043_OUT_Crop_Level		X	82.67	86.65	48
P1010044_IN_Crop_Level	X		98.99	80.49	91
P1010045_OUT_Crop_Level		X	81.19	80.45	61
P1010046_IN_Crop_Level	X		99.0	85.45	90
P1010047_OUT_Crop_Level		X	89.64	80.20	78
P1010048_IN_Crop_Level	X		105.07	86.72	100
P1010049_OUT_Crop_Level		X	79.51	82.46	57
P1010050_IN_Crop_Level	X		106.0	84.91	101
P1010051_OUT_Crop_Level		X	88.91	79.39	80
P1010052_IN_Crop_Level	X		103.09	83.20	103
P1010053_OUT_Crop_Level		X	72.67	79.23	48
P1010054_IN_Crop_Level	X		109.61	82.42	113
P1010055_OUT_Crop_Level		X	67.30	81.62	31
P1010056_IN_Crop_Level	X		105.47	85.15	102
P1010057_OUT_Crop_Level		X	76.55	81.39	47
P1010058_IN_Crop_Level	X		95.82	83.73	85
P1010059_OUT_Crop_Level		X	67.62	85.28	13
P1010060_IN_Crop_Level	X		102.52	86.27	94
P1010061_OUT_Crop_Level		X	73.09	79.20	47
P1010062_IN_Crop_Level	X		105.11	83.79	104
P1010063_OUT_Crop_Level		X	80.89	78.68	72
P1010064_IN_Crop_Level	X		106.59	84.19	102
P1010065_OUT_Crop_Level		X	105.01	82.32	104
P1010066_IN_Crop_Level	X		98.36	84.14	93
P1010067_OUT_Crop_Level		X	82.56	80.50	61
P1010068_IN_Crop_Level	X		104.94	82.61	102

Table B-2. Statistical evaluation for normality of albedo measurements in track scars.

	N Statistic	Minimum Statistic	Maximum Statistic	Mean Statistic	Std. Deviation Statistic	Skewness Statistic	Std. Error	Kurtosis Statistic	Std. Error
ALBEDO IN	33	79.56	109.61	99.3894	7.8674	-1.259	.409	.869	.798

Table B-3. Statistical evaluation for normality of albedo measurements on undisturbed pavement.

	N Statistic	Minimum Statistic	Maximum Statistic	Mean Statistic	Std. Deviation Statistic	Skewness Statistic	Std. Error	Kurtosis Statistic	Std. Error
ALBEDO OUT	33	56.67	105.01	78.1073	10.7517	-.360	.409	.040	.798

Table B-4. Group statistics for albedo measurements in track scars and undisturbed pavement.

	2 OUT	N	Mean	Std. Deviation	Std. Error Mean
Albedo Mean	1.00	33	99.3894	7.8674	1.3695
	2.00	34	78.2026	10.6021	1.8182

Table B-5. Independent samples test comparing albedo measurements.

		Levene's Test for Equality of Variances		t-test for Equality of Means					95% Confidence Interval of the Difference	
		F	Sig.	t	df	Sig. (2-tailed)	Mean Difference	Std. Error Difference	Lower	Upper
Albedo Mean	Equal variances assumed	2.569	.114	9.267	65	.000	21.1867	2.2863	16.6206	25.7529
	Equal variances not assumed			9.307	60.864	.000	21.1867	2.2763	16.6347	25.7387

APPENDIX C

ROCK COATING VALUES

Table C-1. Rock coating values (after Palmer, 2002). 63 images inside and outside of track scars were examined to determine rock varnish particle coverage. NC indicates no varnish present, MN represents presence of magnanese varnish, and FE iron oxide varnish. The strength of varnish coatings on each particle was assigned a weighted value (Table 4-7). The data in this chart indicates total weighted values for each image.

Image	1in 2out	# Particles	NC	MN	FE
4	1	11	40	1	1
6	1	13	44	1	2
8	1	13	36	4	3
10	1	14	44	3	8
12	1	15	40	11	7
14	1	16	44	11	3
16	1	12	36	8	2
18	1	15	60	1	1
20	1	11	44	1	1
22	1	17	60	4	1
24	1	12	32	4	4
26	1	13	40	1	3
28	1	17	68	1	1
30	1	14	24	11	6
32	1	13	40	1	6
34	1	8	28	4	1
36	1	6	16	6	1
38	1	18	72	1	1
40	1	18	40	7	1
42	1	12	72	1	1
44	1	15	56	1	4
46	1	19	76	1	1
48	1	20	72	1	3
50	1	20	76	4	1
52	1	16	36	6	4
54	1	18	12	6	1
56	1	22	32	4	4
58	1	21	24	19	1
60	1	19	12	3	1
62	1	16	12	10	1
64	1	20	28	2	3
66	1	20	20	3	1
68	1	19	68	8	1
Total	34 IN	513	1404	150	80

Image	1in 2out	# Particles	NC	MN	FE
3	2	9	16	9	8
5	2	6	12	3	4
7	2	9	16	11	3
9	2	7	12	9	4
11	2	8	12	11	7
13	2	8	16	7	8
15	2	9	16	16	5
17	2	7	12	12	4
19	2	8	12	6	9
21	2	9	12	6	11
23	2	9	12	8	8
25	2	10	16	12	5
27	2	5	8	8	4
29	2	8	12	13	1
31	2	10	16	16	2
33	2	6	20	1	3
35	2	8	28	4	1
37	2	4	12	1	4
39	2	12	40	4	1
41	2	7	16	6	3
43	2	7	20	6	1
45	2	7	4	8	9
47	2	8	24	5	1
49	2	9	16	12	1
51	2	12	56	4	1
53	2	7	56	1	5
55	2	10	68	1	1
57	2	13	80	1	3
59	2	5	76	4	2
61	2	6	76	1	1
63	2	9	64	1	1
65	2	7	76	3	1
67	2	7	24	4	1
Total	34 OUT	266	966	214	123

APPENDIX D

MICROTOPOGRAPHY

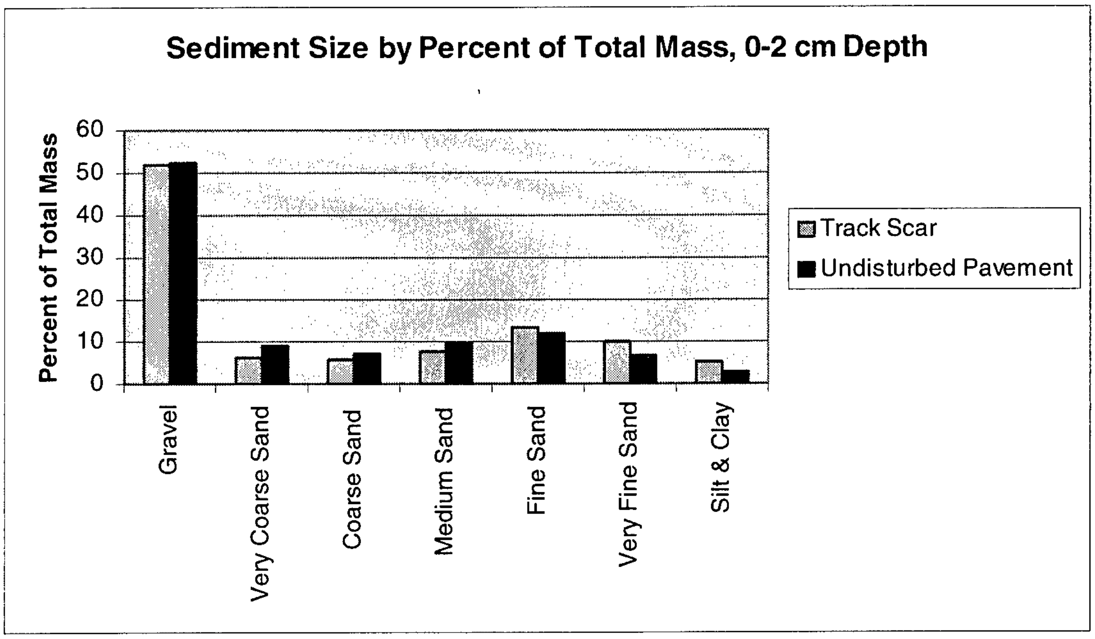
Table D-1. These values represent measurements taken in the field of the deepest portion of track scar ruts. Measurements are in cm.

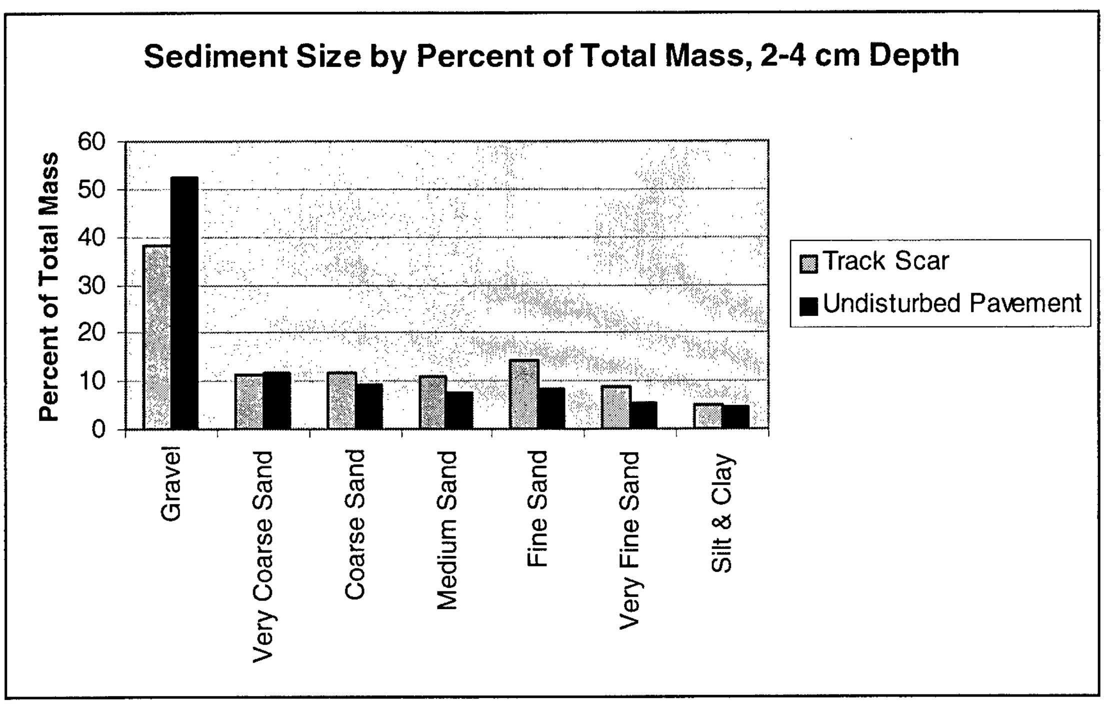
0.4	0.2	0.5	1.2
0.4	0.2	1.1	0.4
1.7	0.3	0.8	0.2
0.3	0.5	0.8	1.0
0.4	0.5	1.5	1.0
1.8	0.5	0.7	0.6
0.7	0.7	1.0	1.5
2.0	0.8	1.5	0.8
0.3	1.0	0.3	0.4
0.4	1.0	0.4	2.1
0.5	1.0	0.2	2.5
0.5	1.2	1.1	1.5
0.4	1.5	1.0	1.7
1.3	1.5	0.3	
1.1	1.7	0.2	
1.1	2.2	1.6	Avg: .925 cm

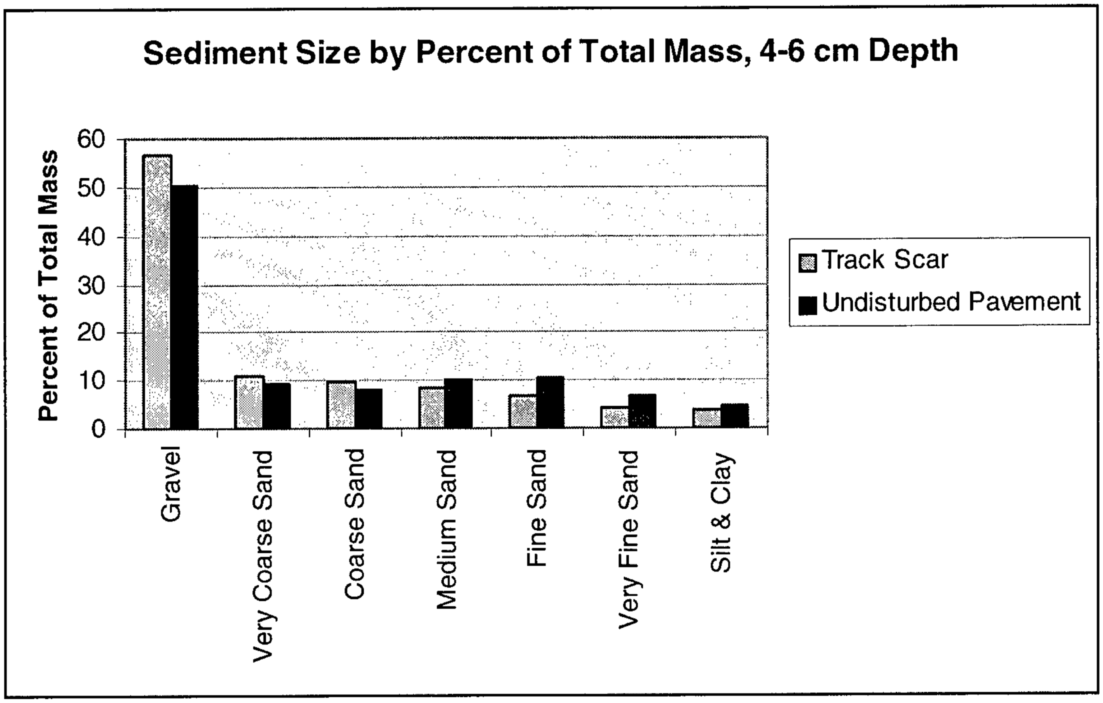
APPENDIX E

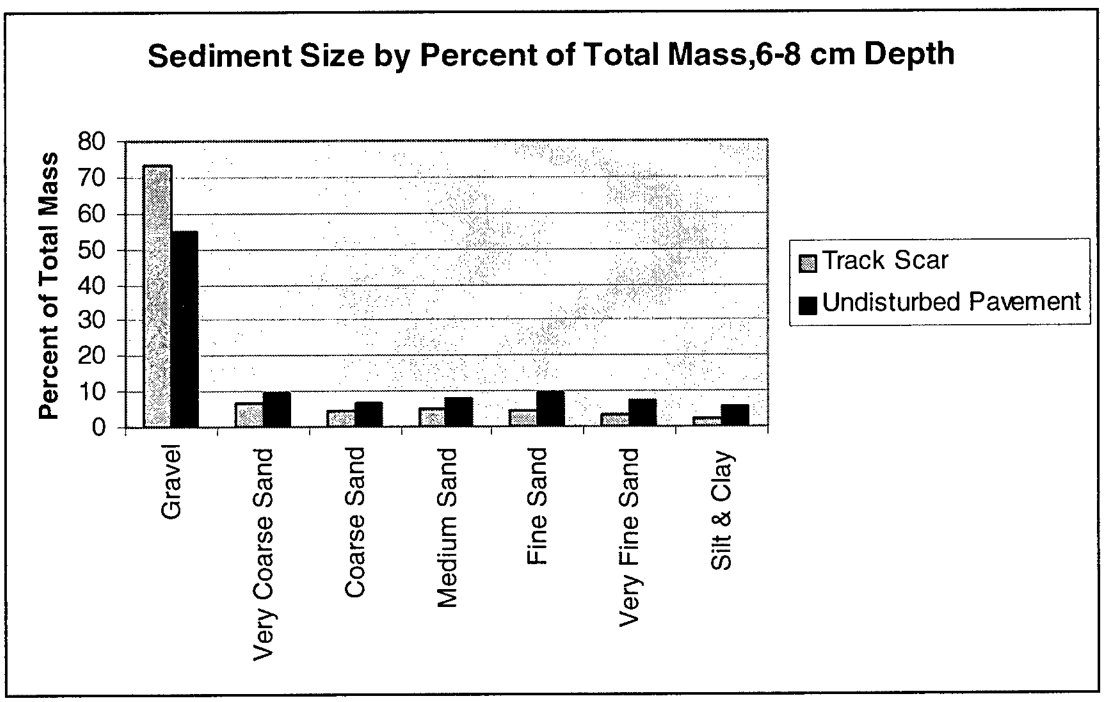
SEDIMENT SIEVE RESULTS

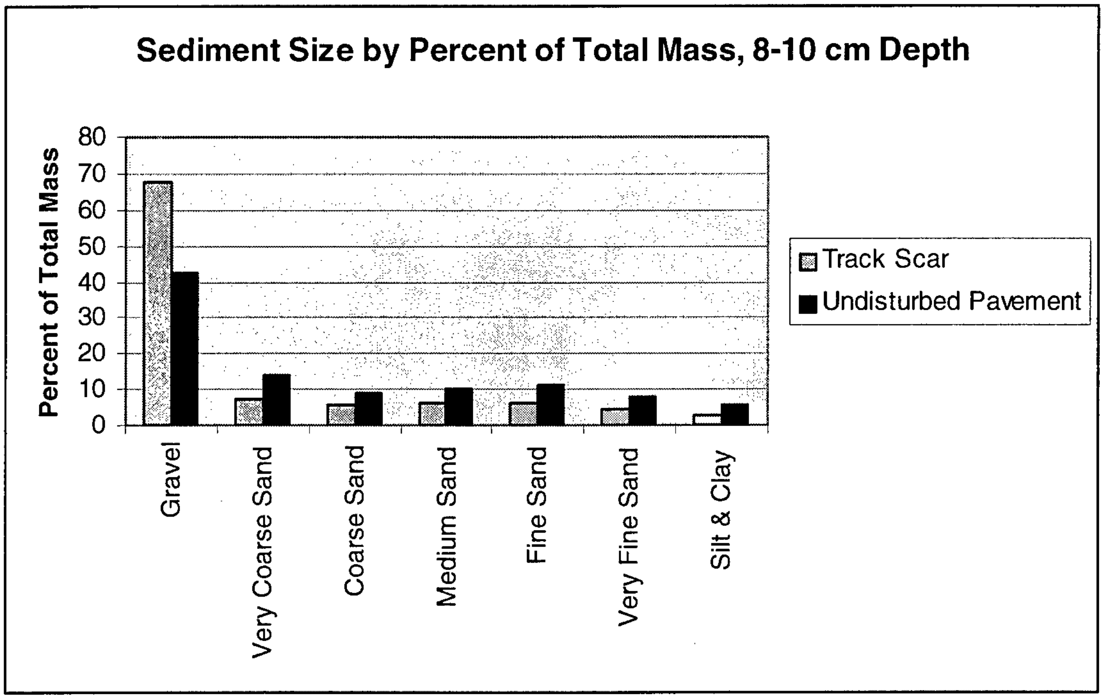
Figure E-1. The following charts compare the proportion (expressed as a percentage of total mass) of sediment of varying sizes from samples taken beneath track scars and beneath undisturbed desert pavement. Sediment samples were dried, weighed, sieved to divide grain sizes, and each subset was weighed again. Sediment was taken at 2 cm depths from 0-12 cm.

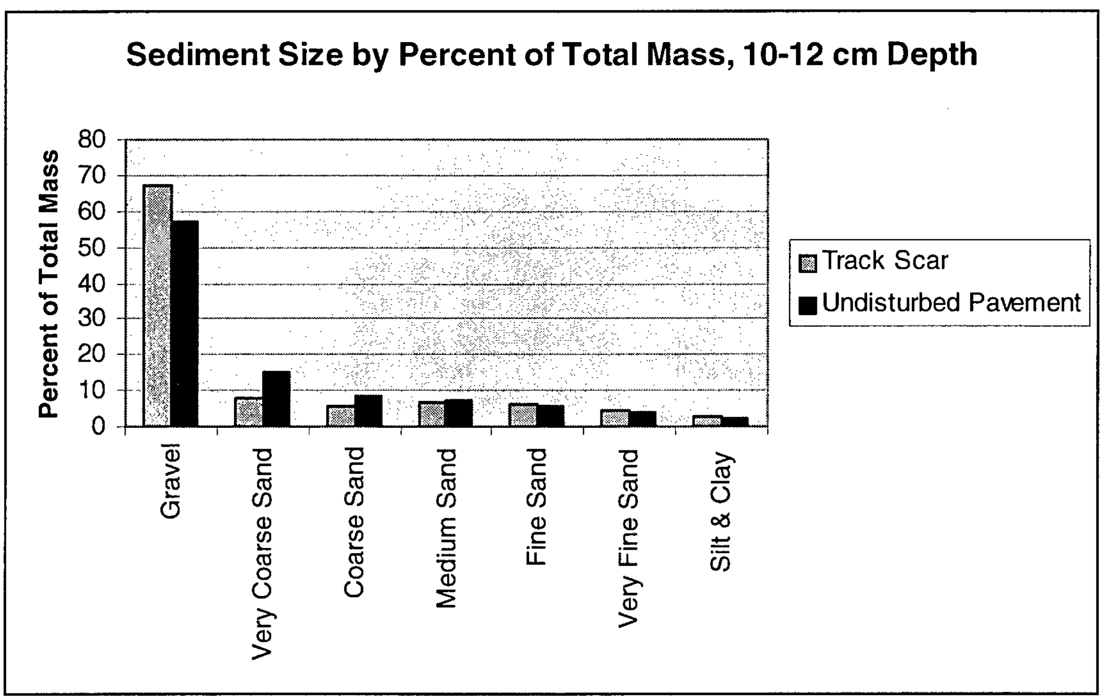





Sediment Size by Percent of Total Mass, 4-6 cm Depth
Percent of Total Mass
60
50
40
30
20
10
0
Gravel
Very Coarse Sand
Coarse Sand
Medium Sand
Fine Sand
Very Fine Sand
Silt & Clay
Track Scar
Undisturbed Pavement


Sediment Size by Percent of Total Mass,6-8 cm Depth
Percent of Total Mass
80
70
60
50
40
30
20
10
0
Gravel
Very Coarse Sand
Coarse Sand
Medium Sand
Fine Sand
Very Fine Sand
Silt & Clay
Track Scar
Undisturbed Pavement


Sediment Size by Percent of Total Mass, 8-10 cm Depth
Percent of Total Mass
80
70
60
50
40
30
20
10
0
Gravel
Very Coarse Sand
Coarse Sand
Medium Sand
Fine Sand
Very Fine Sand
Silt & Clay
Track Scar
Undisturbed Pavement


Sediment Size by Percent of Total Mass, 10-12 cm Depth
Percent of Total Mass
80
70
60
50
40
30
20
10
0
Gravel
Very Coarse Sand
Coarse Sand
Medium Sand
Fine Sand
Very Fine Sand
Silt & Clay
Track Scar
Undisturbed Pavement

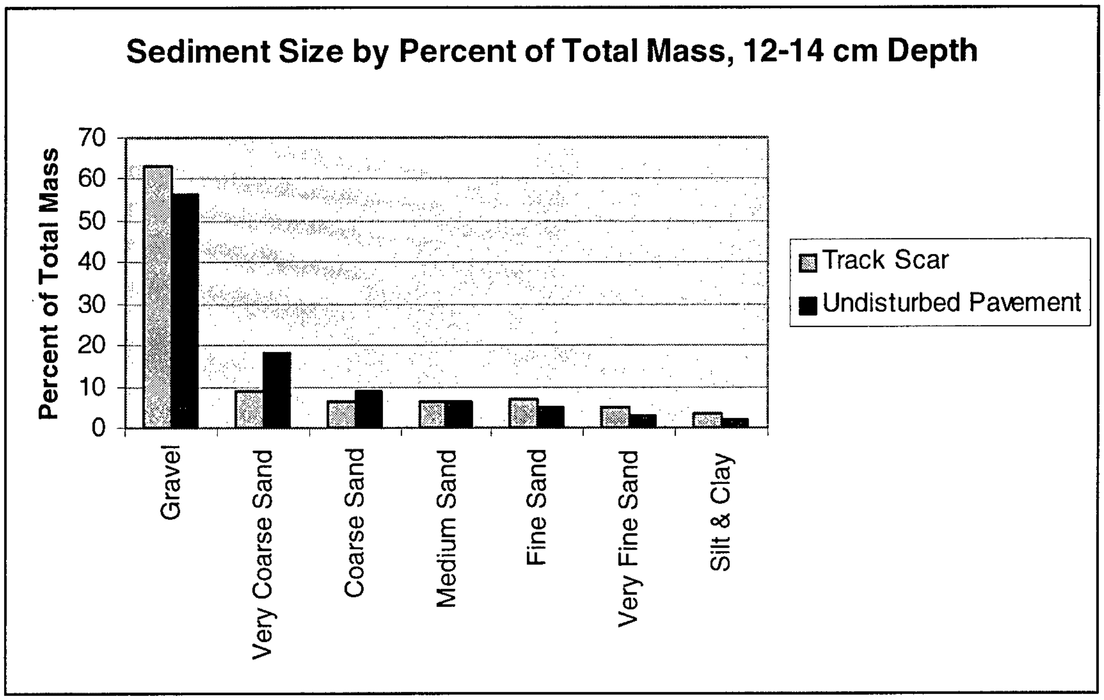

Sediment Size by Percent of Total Mass, 12-14 cm Depth
Percent of Total Mass
70
60
50
40
30
20
10
0
Gravel
Very Coarse Sand
Coarse Sand
Medium Sand
Fine Sand
Very Fine Sand
Silt & Clay
Track Scar
Undisturbed Pavement

Table E-1. Sediment samples were obtained at 2 cm intervals from 0 – 12 cm in depth in both track scarred pavement and undisturbed pavement. All samples were dried in an oven for three hours before sieving. "Sample Percent" reflects the percent of the mass of the constituent sediment size to the total sample mass in percent.

Sample: 031107 IN Top 2 cm — Mass in grams

ASTM E-11 Scale	PHI Scale	Sample + Container	Container Mass	Sample Mass	Sample Percent
Gravel #10	-1	110.6	5.5	105.1	51.6%
Very Coarse Sand #18	0	18.0	5.5	12.5	6.1%
Coarse Sand #35	1	16.8	5.6	11.2	5.5%
Medium Sand #60	2	21.2	5.6	15.6	7.7%
Fine Sand #120	3	32.8	5.7	27.1	13.3%
Very Fine Sand #230	4	26.3	5.6	20.7	10.2%
Silt and Clay	5 and over	16.8	5.5	11.3	5.6%
Total Sample		209.0	5.5	203.5	100.0%

Sample: 031107 OUT Top 2 cm — Mass in grams

ASTM E-11 Scale	PHI Scale	Sample + Container	Container Mass	Sample Mass	Sample Percent
Gravel #10	-1	83.0	5.5	77.5	52.4%
Very Coarse Sand #18	0	18.9	5.5	13.4	9.1%
Coarse Sand #35	1	15.6	5.6	10	6.8%
Medium Sand #60	2	19.8	5.6	14.2	9.6%
Fine Sand #120	3	23.3	5.7	17.6	11.9%
Very Fine Sand #230	4	15.1	5.6	9.5	6.4%
Silt and Clay	5 and over	10.2	5.5	4.7	3.2%
Total Sample		153.3	5.5	147.8	100.0%

Sample: 031108 IN 2-4 cm — Mass in grams

ASTM E-11 Scale	PHI Scale	Sample + Container	Container Mass	Sample Mass	Sample Percent
Gravel #10	-1	51.3	5.5	45.8	37.9%
Very Coarse Sand #18	0	19.4	5.5	13.9	11.5%
Coarse Sand #35	1	19.4	5.6	13.8	11.4%
Medium Sand #60	2	18.9	5.6	13.3	11.0%
Fine Sand #120	3	22.9	5.7	17.2	14.2%
Very Fine Sand #230	4	16.6	5.6	11	9.1%
Silt and Clay	5 and over	11.8	5.5	6.3	5.2%
Total Sample		126.5	5.5	121	100.0%

Sample: 031108 OUT 2-4 cm — Mass in grams

ASTM E-11 Scale	PHI Scale	Sample + Container	Container Mass	Sample Mass	Sample Percent
Gravel #10	-1	107.5	5.5	102	52.3%
Very Coarse Sand #18	0	28.5	5.5	23	11.8%
Coarse Sand #35	1	23.4	5.6	17.8	9.1%
Medium Sand #60	2	20.5	5.6	14.9	7.6%
Fine Sand #120	3	21.5	5.7	15.8	8.1%
Very Fine Sand #230	4	16.5	5.6	10.9	5.6%
Silt and Clay	5 and over	14.7	5.5	9.2	4.7%
Total Sample		200.7	5.5	195.2	100.0%

Sample: 031110 IN 4-6 cm — Mass in grams

ASTM E-11 Scale	PHI Scale	Sample + Container	Container Mass	Sample Mass	Sample Percent
Gravel #10	-1	68.4	5.5	62.9	56.4%
Very Coarse Sand #18	0	17.4	5.5	11.9	10.7%
Coarse Sand #35	1	16.4	5.6	10.8	9.7%
Medium Sand #60	2	14.8	5.6	9.2	8.2%
Fine Sand #120	3	13.3	5.7	7.6	6.8%
Very Fine Sand #230	4	10.1	5.6	4.5	4.0%
Silt and Clay	5 and over	9.7	5.5	4.2	3.8%
Total Sample		117.1	5.5	111.6	100.0%

Sample: 031110 OUT 4-6 cm — Mass in grams

ASTM E-11 Scale	PHI Scale	Sample + Container	Container Mass	Sample Mass	Sample Percent
Gravel #10	-1	81.2	5.5	75.7	50.5%
Very Coarse Sand #18	0	19.4	5.5	13.9	9.3%
Coarse Sand #35	1	17.7	5.6	12.1	8.1%
Medium Sand #60	2	20.5	5.6	14.9	9.9%
Fine Sand #120	3	21.3	5.7	15.6	10.4%
Very Fine Sand #230	4	16.0	5.6	10.4	6.9%
Silt and Clay	5 and over	12.4	5.5	6.9	4.6%
Total Sample		155.4	5.5	149.9	100.0%

Sample: 031111 IN 6-8 cm — Mass in grams

ASTM E-11 Scale	PHI Scale	Sample + Container	Container Mass	Sample Mass	Sample Percent
Gravel #10	-1	146.1	5.5	140.6	73.5%
Very Coarse Sand #18	0	18.3	5.5	12.8	6.7%
Coarse Sand #35	1	14.6	5.6	9	4.7%
Medium Sand #60	2	15.0	5.6	9.4	4.9%
Fine Sand #120	3	14.8	5.7	9.1	4.8%
Very Fine Sand #230	4	11.9	5.6	6.3	3.3%
Silt and Clay	5 and over	9.9	5.5	4.4	2.3%
Total Sample		196.7	5.5	191.2	100.0%

Sample: 031111 OUT 6-8 cm — Mass in grams

ASTM E-11 Scale	PHI Scale	Sample + Container	Container Mass	Sample Mass	Sample Percent
Gravel #10	-1	119.7	5.5	114.2	54.8%
Very Coarse Sand #18	0	25.2	5.5	19.7	9.5%
Coarse Sand #35	1	18.8	5.6	13.2	6.3%
Medium Sand #60	2	22.1	5.6	16.5	7.9%
Fine Sand #120	3	25.0	5.7	19.3	9.3%
Very Fine Sand #230	4	20.5	5.6	14.9	7.1%
Silt and Clay	5 and over	16.9	5.5	11.4	5.5%
Total Sample		213.9	5.5	208.4	100.0%

Sample: 031113 IN 8-10 cm — Mass in grams

ASTM E-11 Scale	PHI Scale	Sample + Container	Container Mass	Sample Mass	Sample Percent
Gravel #10	-1	100.3	5.5	94.8	68.0%
Very Coarse Sand #18	0	15.6	5.5	10.1	7.2%
Coarse Sand #35	1	13.1	5.6	7.5	5.4%
Medium Sand #60	2	13.9	5.6	8.3	5.9%
Fine Sand #120	3	14.4	5.7	8.7	6.2%
Very Fine Sand #230	4	11.6	5.6	6	4.3%
Silt and Clay	5 and over	9.7	5.5	4.2	3.0%
Total Sample		145.0	5.5	139.5	100.0%

Sample: 031113 OUT 8-10 cm — Mass in grams

ASTM E-11 Scale	PHI Scale	Sample + Container	Container Mass	Sample Mass	Sample Percent
Gravel #10	-1	83.2	5.5	77.7	42.5%
Very Coarse Sand #18	0	31.3	5.5	25.8	14.1%
Coarse Sand #35	1	21.1	5.6	15.5	8.5%
Medium Sand #60	2	24.2	5.6	18.6	10.2%
Fine Sand #120	3	26.0	5.7	20.3	11.1%
Very Fine Sand #230	4	20.0	5.6	14.4	7.9%
Silt and Clay	5 and over	15.9	5.5	10.4	5.7%
Total Sample		188.5	5.5	183	100.0%

Sample: 031115 IN 10-12 cm

Mass in grams

ASTM E-11 Scale	**PHI** Scale	Sample + Container	Container Mass	Sample Mass	Sample Percent
Gravel #10	-1	125.8	5.5	120.3	67.1%
Very Coarse Sand #18	0	19.0	5.5	13.5	7.5%
Coarse Sand #35	1	15.7	5.6	10.1	5.6%
Medium Sand #60	2	17.0	5.6	11.4	6.4%
Fine Sand #120	3	16.3	5.7	10.6	5.9%
Very Fine Sand #230	4	13.5	5.6	7.9	4.4%
Silt and Clay	5 and over	11.1	5.5	5.6	3.1%
Total Sample		184.9	5.5	179.4	100.0%

Sample: 031115 OUT 10-12 cm

Mass in grams

ASTM E-11 Scale	PHI Scale	Sample + Container	Container Mass	Sample Mass	Sample Percent
Gravel #10	-1	97.0	5.5	91.5	57.1%
Very Coarse Sand #18	0	29.8	5.5	24.3	15.2%
Coarse Sand #35	1	18.7	5.6	13.1	8.2%
Medium Sand #60	2	16.8	5.6	11.2	7.0%
Fine Sand #120	3	14.7	5.7	9	5.6%
Very Fine Sand #230	4	12.0	5.6	6.4	4.0%
Silt and Clay	5 and over	9.5	5.5	4	2.5%
Total Sample		165.8	5.5	160.3	100.0%

Sample: 031118 IN 12-14 cm

Mass in grams

ASTM E-11 Scale	PHI Scale	Sample + Container	Container Mass	Sample Mass	Sample Percent
Gravel #10	-1	137.8	5.5	132.3	63.4%
Very Coarse Sand #18	0	23.9	5.5	18.4	8.8%
Coarse Sand #35	1	18.2	5.6	12.6	6.0%
Medium Sand #60	2	19.1	5.6	13.5	6.5%
Fine Sand #120	3	19.7	5.7	14	6.7%
Very Fine Sand #230	4	16.3	5.6	10.7	5.1%
Silt and Clay	5 and over	12.6	5.5	7.1	3.4%
Total Sample		214.2	5.5	208.7	100.0%

Sample: 031118 OUT 12-14 cm

Mass in grams

ASTM E-11 Scale	PHI Scale	Sample + Container	Container Mass	Sample Mass	Sample Percent
Gravel #10	-1	111.5	5.5	106	56.1%
Very Coarse Sand #18	0	39.8	5.5	34.3	18.2%
Coarse Sand #35	1	22.3	5.6	16.7	8.8%
Medium Sand #60	2	17.8	5.6	12.2	6.5%
Fine Sand #120	3	15.2	5.7	9.5	5.0%
Very Fine Sand #230	4	11.5	5.6	5.9	3.1%
Silt and Clay	5 and over	9.1	5.5	3.6	1.9%
Total Sample		194.4	5.5	188.9	100.0%

Sample: 030944 IN 0-2 cm — All mass in grams

ASTM E-11 Scale	PHI Scale	Sample + Container	Container Mass	Sample Mass	Sample Percent
Gravel #10	-1	42.4	5.5	36.9	29.1%
Very Coarse Sand #18	0	19.0	5.5	13.5	10.7%
Coarse Sand #35	1	16.9	5.6	11.3	8.9%
Medium Sand #60	2	16.8	5.6	11.2	8.8%
Fine Sand #120	3	23.0	5.7	17.3	13.7%
Very Fine Sand #230	4	25.1	5.6	19.5	15.4%
Silt and Clay	5 and over	22.1	5.5	16.6	13.1%
Total Sample		132.1	5.5	126.6	100.0%

Sample: 030944 OUT 0-2 cm — All mass in grams

ASTM E-11 Scale	PHI Scale	Sample + Container	Container Mass	Sample Mass	Sample Percent
Gravel #10	-1	99.1	5.5	93.6	57.4%
Very Coarse Sand #18	0	21.9	5.5	16.4	10.1%
Coarse Sand #35	1	16.2	5.6	10.6	6.5%
Medium Sand #60	2	14.7	5.6	9.1	5.6%
Fine Sand #120	3	20.7	5.7	15	9.2%
Very Fine Sand #230	4	18.1	5.6	12.5	7.7%
Silt and Clay	5 and over	10.7	5.5	5.2	3.2%
Total Sample		168.5	5.5	163	100.0%

Sample: 031010 IN 2-4 cm					All mass in grams
ASTM E-11 Scale	PHI Scale	Sample + Container	Container Mass	Sample Mass	Sample Percent
Gravel #10	-1	42.9	5.5	37.4	43.6%
Very Coarse Sand #18	0	13.4	5.5	7.9	9.2%
Coarse Sand #35	1	13.4	5.6	7.8	9.1%
Medium Sand #60	2	14.7	5.6	9.1	10.6%
Fine Sand #120	3	18.0	5.7	12.3	14.4%
Very Fine Sand #230	4	14.1	5.6	8.5	9.9%
Silt and Clay	5 and over	9.0	5.5	3.5	4.1%
Total Sample		91.2	5.5	85.7	100.0%

Sample: 031011 OUT 2-4 cm					All mass in grams
ASTM E-11 Scale	PHI Scale	Sample + Container	Container Mass	Sample Mass	Sample Percent
Gravel #10	-1	96.6	5.5	91.1	50.4%
Very Coarse Sand #18	0	28.9	5.5	23.4	12.9%
Coarse Sand #35	1	24.1	5.6	18.5	10.2%
Medium Sand #60	2	21.4	5.6	15.8	8.7%
Fine Sand #120	3	24.5	5.7	18.8	10.4%
Very Fine Sand #230	4	13.7	5.6	8.1	4.5%
Silt and Clay	5 and over	9.1	5.5	3.6	2.0%
Total Sample		186.2	5.5	180.7	100.0%

Sample: 031012 IN 4-6 cm — All mass in grams

ASTM E-11 Scale	PHI Scale	Sample + Container	Container Mass	Sample Mass	Sample Percent
Gravel #10	-1	105.1	5.5	99.6	57.1%
Very Coarse Sand #18	0	29.7	5.5	24.2	13.9%
Coarse Sand #35	1	23.5	5.6	17.9	10.3%
Medium Sand #60	2	18.8	5.6	13.2	7.6%
Fine Sand #120	3	16.1	5.7	10.4	6.0%
Very Fine Sand #230	4	10.6	5.6	5	2.9%
Silt and Clay	5 and over	8.7	5.5	3.2	1.8%
Total Sample		180.0	5.5	174.5	100.0%

Sample: 031012 OUT 4-6 cm — All mass in grams

ASTM E-11 Scale	PHI Scale	Sample + Container	Container Mass	Sample Mass	Sample Percent
Gravel #10	-1	61.9	5.5	56.4	33.4%
Very Coarse Sand #18	0	32.8	5.5	27.3	16.1%
Coarse Sand #35	1	29.0	5.6	23.4	13.8%
Medium Sand #60	2	29.4	5.6	23.8	14.1%
Fine Sand #120	3	28.0	5.7	22.3	13.2%
Very Fine Sand #230	4	15.6	5.6	10	5.9%
Silt and Clay	5 and over	11.4	5.5	5.9	3.5%
Total Sample		174.6	5.5	169.1	100.0%

Sample: 030955 IN 6-8 cm

All mass in grams

ASTM E-11 Scale	PHI Scale	Sample + Container	Container Mass	Sample Mass	Sample Percent
Gravel #10	-1	81.0	5.5	75.5	58.3%
Very Coarse Sand #18	0	19.9	5.5	14.4	11.1%
Coarse Sand #35	1	14.5	5.6	8.9	6.9%
Medium Sand #60	2	14.7	5.6	9.1	7.0%
Fine Sand #120	3	15.3	5.7	9.6	7.4%
Very Fine Sand #230	4	11.2	5.6	5.6	4.3%
Silt and Clay	5 and over	10.9	5.5	5.4	4.2%
Total Sample		135.1	5.5	129.6	100.0%

Sample: 030955 OUT 6-8 cm

All mass in grams

ASTM E-11 Scale	PHI Scale	Sample + Container	Container Mass	Sample Mass	Sample Percent
Gravel #10	-1	54.1	5.5	48.6	28.3%
Very Coarse Sand #18	0	25.4	5.5	19.9	11.6%
Coarse Sand #35	1	25.7	5.6	20.1	11.7%
Medium Sand #60	2	32.1	5.6	26.5	15.4%
Fine Sand #120	3	37.5	5.7	31.8	18.5%
Very Fine Sand #230	4	17.7	5.6	12.1	7.0%
Silt and Clay	5 and over	16.9	5.5	11.4	6.6%
Total Sample		177.3	5.5	171.8	100.0%

Sample: 031020 IN 8-10 cm — All mass in grams

ASTM E-11 Scale	PHI Scale	Sample + Container	Container Mass	Sample Mass	Sample Percent
Gravel #10	-1	40.1	5.5	34.6	30.7%
Very Coarse Sand #18	0	17.5	5.5	12	10.6%
Coarse Sand #35	1	17.1	5.6	11.5	10.2%
Medium Sand #60	2	20.3	5.6	14.7	13.0%
Fine Sand #120	3	22.6	5.7	16.9	15.0%
Very Fine Sand #230	4	16.9	5.6	11.3	10.0%
Silt and Clay	5 and over	17.5	5.5	12	10.6%
Total Sample		118.2	5.5	112.7	100.0%

Sample: 031020 OUT 8-10 cm — All mass in grams

ASTM E-11 Scale	PHI Scale	Sample + Container	Container Mass	Sample Mass	Sample Percent
Gravel #10	-1	56.2	5.5	50.7	40.5%
Very Coarse Sand #18	0	19.3	5.5	13.8	11.0%
Coarse Sand #35	1	18.1	5.6	12.5	10.0%
Medium Sand #60	2	20.9	5.6	15.3	12.2%
Fine Sand #120	3	20.5	5.7	14.8	11.8%
Very Fine Sand #230	4	15.8	5.6	10.2	8.1%
Silt and Clay	5 and over	13.9	5.5	8.4	6.7%
Total Sample		130.7	5.5	125.2	100.0%

Sample: 030945 IN 0-2cm — All mass in grams

ASTM E-11 Scale	PHI Scale	Sample + Container	Container Mass	Sample Mass	Sample Percent
Gravel #10	-1	40.8	5.5	35.3	26.5%
Very Coarse Sand #18	0	20.6	5.5	15.1	11.3%
Coarse Sand #35	1	18.6	5.6	13	9.8%
Medium Sand #60	2	18.4	5.6	12.8	9.6%
Fine Sand #120	3	28.4	5.7	22.7	17.0%
Very Fine Sand #230	4	20.3	5.6	14.7	11.0%
Silt and Clay	5 and over	25.3	5.5	19.8	14.9%
Total Sample		138.8	5.5	133.3	100.0%

Sample: 030945 OUT 0-2 cm — All mass in grams

ASTM E-11 Scale	PHI Scale	Sample + Container	Container Mass	Sample Mass	Sample Percent
Gravel #10	-1	75.7	5.5	70.2	45.2%
Very Coarse Sand #18	0	23.3	5.5	17.8	11.5%
Coarse Sand #35	1	17.4	5.6	11.8	7.6%
Medium Sand #60	2	19.9	5.6	14.3	9.2%
Fine Sand #120	3	16.5	5.7	10.8	7.0%
Very Fine Sand #230	4	22.3	5.6	16.7	10.8%
Silt and Clay	5 and over	17.1	5.5	11.6	7.5%
Total Sample		160.8	5.5	155.3	100.0%

Sample: 030946 IN 2-4 cm — All mass in grams

ASTM E-11 Scale	PHI Scale	Sample + Container	Container Mass	Sample Mass	Sample Percent
Gravel #10	-1	54.0	5.5	48.5	31.9%
Very Coarse Sand #18	0	34.9	5.5	29.4	19.4%
Coarse Sand #35	1	23.5	5.6	17.9	11.8%
Medium Sand #60	2	18.6	5.6	13	8.6%
Fine Sand #120	3	20.0	5.7	14.3	9.4%
Very Fine Sand #230	4	22.5	5.6	16.9	11.1%
Silt and Clay	5 and over	17.1	5.5	11.6	7.6%
Total Sample		157.3	5.5	151.8	100.0%

Sample: 030946 OUT 2-4 cm — All mass in grams

ASTM E-11 Scale	PHI Scale	Sample + Container	Container Mass	Sample Mass	Sample Percent
Gravel #10	-1	100.4	5.5	94.9	57.3%
Very Coarse Sand #18	0	23.3	5.5	17.8	10.8%
Coarse Sand #35	1	18.6	5.6	13	7.9%
Medium Sand #60	2	17.9	5.6	12.3	7.4%
Fine Sand #120	3	20.6	5.7	14.9	9.0%
Very Fine Sand #230	4	13.4	5.6	7.8	4.7%
Silt and Clay	5 and over	9.7	5.5	4.2	2.5%
Total Sample		171.0	5.5	165.5	100.0%

Sample: 030952 IN 4-6 cm					All mass in grams
ASTM E-11 Scale	PHI Scale	Sample + Container	Container Mass	Sample Mass	Sample Percent
Gravel #10	-1	265.2	5.5	259.7	61.0%
Very Coarse Sand #18	0	64.1	5.5	58.6	13.8%
Coarse Sand #35	1	37.0	5.6	31.4	7.4%
Medium Sand #60	2	31.7	5.6	26.1	6.1%
Fine Sand #120	3	30.0	5.7	24.3	5.7%
Very Fine Sand #230	4	19.1	5.6	13.5	3.2%
Silt and Clay	5 and over	15.9	5.5	10.4	2.4%
Total Sample		430.9	5.5	425.4	100.0%

Sample: 030952 OUT 4-6 cm					All mass in grams
ASTM E-11 Scale	PHI Scale	Sample + Container	Container Mass	Sample Mass	Sample Percent
Gravel #10	-1	98.2	5.5	92.7	53.6%
Very Coarse Sand #18	0	24.5	5.5	19	11.0%
Coarse Sand #35	1	22.5	5.6	16.9	9.8%
Medium Sand #60	2	22.8	5.6	17.2	9.9%
Fine Sand #120	3	20.4	5.7	14.7	8.5%
Very Fine Sand #230	4	13.5	5.6	7.9	4.6%
Silt and Clay	5 and over	10.4	5.5	4.9	2.8%
Total Sample		178.6	5.5	173.1	100.0%

Sample: 031019 IN 6-8 cm					All mass in grams
ASTM E-11 Scale	PHI Scale	Sample + Container	Container Mass	Sample Mass	Sample Percent
Gravel #10	-1	64.3	5.5	58.8	44.4%
Very Coarse Sand #18	0	21.3	5.5	15.8	11.9%
Coarse Sand #35	1	16.6	5.6	11	8.3%
Medium Sand #60	2	17.8	5.6	12.2	9.2%
Fine Sand #120	3	21.0	5.7	15.3	11.6%
Very Fine Sand #230	4	16.1	5.6	10.5	7.9%
Silt and Clay	5 and over	14.4	5.5	8.9	6.7%
Total Sample		137.9	5.5	132.4	100.0%

Sample: 031019 OUT 6-8 cm					All mass in grams
ASTM E-11 Scale	PHI Scale	Sample + Container	Container Mass	Sample Mass	Sample Percent
Gravel #10	-1	53.6	5.5	48.1	41.3%
Very Coarse Sand #18	0	19.5	5.5	14	12.0%
Coarse Sand #35	1	19.0	5.6	13.4	11.5%
Medium Sand #60	2	20.4	5.6	14.8	12.7%
Fine Sand #120	3	18.9	5.7	13.2	11.3%
Very Fine Sand #230	4	12.8	5.6	7.2	6.2%
Silt and Clay	5 and over	10.9	5.5	5.4	4.6%
Total Sample		122.1	5.5	116.6	100.0%

Sample: 030959 IN 8-10 cm					All mass in grams
ASTM E-11 Scale	PHI Scale	Sample + Container	Container Mass	Sample Mass	Sample Percent
Gravel #10	-1	98.5	5.5	93	68.5%
Very Coarse Sand #18	0	15.4	5.5	9.9	7.3%
Coarse Sand #35	1	12.1	5.6	6.5	4.8%
Medium Sand #60	2	13.0	5.6	7.4	5.5%
Fine Sand #120	3	13.4	5.7	7.7	5.7%
Very Fine Sand #230	4	11.5	5.6	5.9	4.3%
Silt and Clay	5 and over	10.8	5.5	5.3	3.9%
Total Sample		141.2	5.5	135.7	100.0%

Sample: 030959 OUT 8-10 cm					All mass in grams
ASTM E-11 Scale	PHI Scale	Sample + Container	Container Mass	Sample Mass	Sample Percent
Gravel #10	-1	62.4	5.5	56.9	42.1%
Very Coarse Sand #18	0	20.9	5.5	15.4	11.4%
Coarse Sand #35	1	18.9	5.6	13.3	9.8%
Medium Sand #60	2	21.2	5.6	15.6	11.5%
Fine Sand #120	3	22.1	5.7	16.4	12.1%
Very Fine Sand #230	4	14.4	5.6	8.8	6.5%
Silt and Clay	5 and over	14.6	5.5	9.1	6.7%
Total Sample		140.8	5.5	135.3	100.0%

Sample: 031023 IN 10-12 cm — All mass in grams

ASTM E-11 Scale	PHI Scale	Sample + Container	Container Mass	Sample Mass	Sample Percent
Gravel #10	-1	61.3	5.5	55.8	49.1%
Very Coarse Sand #18	0	14.8	5.5	9.3	8.2%
Coarse Sand #35	1	14.0	5.6	8.4	7.4%
Medium Sand #60	2	16.2	5.6	10.6	9.3%
Fine Sand #120	3	17.5	5.7	11.8	10.4%
Very Fine Sand #230	4	14.4	5.6	8.8	7.7%
Silt and Clay	5 and over	13.9	5.5	8.4	7.4%
Total Sample		119.1	5.5	113.6	100.0%

Sample: 031023 OUT 10-12 cm — All mass in grams

ASTM E-11 Scale	PHI Scale	Sample + Container	Container Mass	Sample Mass	Sample Percent
Gravel #10	-1	47.7	5.5	42.2	28.9%
Very Coarse Sand #18	0	23.5	5.5	18	12.3%
Coarse Sand #35	1	23.7	5.6	18.1	12.4%
Medium Sand #60	2	26.3	5.6	20.7	14.2%
Fine Sand #120	3	26.3	5.7	20.6	14.1%
Very Fine Sand #230	4	20.0	5.6	14.4	9.8%
Silt and Clay	5 and over	17.8	5.5	12.3	8.4%
Total Sample		151.7	5.5	146.2	100.0%

APPENDIX F

SOIL DENSITY MEASUREMENTS

Table F-1. Soil density measurements were taken with the Troxler 3430 Roadreader nuclear density gauge. Two paired readings were taken at each site, one under track-scarred areas, and one under adjacent, undisturbed pavement less than 1 meter from the first reading.

Site 1 In track

Depth (In)	Wet Density (lbs/ft^3)	Dry Density (lbs/ft^3)	Moisture (%)	Moisture (lbs/ft^3)
0	121.9	114.4	6.6	7.5
2	122.2	115.7	5.6	6.5
4	121.1	114.6	5.6	6.4
6	121.0	114.3	5.9	6.7
8	121.2	114.4	5.9	6.8

Site 1 Undisturbed Pavement

Depth (In)	Wet Density (lbs/ft^3)	Dry Density (lbs/ft^3)	Moisture (%)	Moisture (lbs/ft^3)
0	118.6	110.9	6.9	7.6
2	117.2	110.0	6.6	7.3
4	119.9	112.5	6.5	7.4
6	120.3	112.1	7.3	8.2
8	121.0	113.4	6.7	7.6

Site 2 In track

Depth (In)	Wet Density (lbs/ft^3)	Dry Density (lbs/ft^3)	Moisture (%)	Moisture (lbs/ft^3)
0	124.4	118.7	4.7	5.6
2	130.0	124.9	4.1	5.2
4	131.0	125.6	4.3	5.4
6	133.6	128.2	4.2	5.4
8	130.6	125.6	4.0	5.0

SITE 2 Undisturbed Pavement

Depth (In)	Wet Density (lbs/ft^3)	Dry Density (lbs/ft^3)	Moisture (%)	Moisture (lbs/ft^3)
0	109.7	102.7	6.8	7.0
2	112.1	105.4	6.4	6.7
4	119.1	112.1	6.2	7.0
6	122.9	115.9	6.0	7.0
8	127.0	120.4	5.5	6.6

SITE 3 in track

Depth (In)	Wet Density (lbs/ft^3)	Dry Density (lbs/ft^3)	Moisture (%)	Moisture (lbs/ft^3)
0	125.5	118.8	5.7	6.7
2	131.4	124.5	5.6	7.0
4	131.3	124.6	5.4	6.7
6	131.6	124.9	5.4	6.7
8	131.6	124.8	5.5	6.8

SITE 3 Undisturbed Pavement

Depth (In)	Wet Density (lbs/ft^3)	Dry Density (lbs/ft^3)	Moisture (%)	Moisture (lbs/ft^3)
0	112.5	106.2	5.9	6.3
2	113.0	106.3	6.2	6.6
4	116.4	110.2	5.7	6.3
6	118.6	112.2	5.7	6.4
8	126.5	120.4	5.0	6.1

SITE 4 In Track

Depth (In)	Wet Density (lbs/ft^3)	Dry Density (lbs/ft^3)	Moisture (%)	Moisture (lbs/ft^3)
0	109.7	101.4	8.3	8.1
2	111.9	103.3	8.3	8.5
4	112.8	104.7	7.7	8.1
6	115.4	107.5	7.4	8.0
8	119.5	110.9	7.8	8.6

SITE 4 Undisturbed Pavement

Depth (In)	Wet Density (lbs/ft^3)	Dry Density (lbs/ft^3)	Moisture (%)	Moisture (lbs/ft^3)
0	105.0	99.2	5.8	5.7
2	108.3	102.5	5.7	5.8
4	110.0	104.4	5.4	5.6
6	111.6	106.0	5.2	5.5
8	116.6	110.9	5.2	5.7

SITE 5 In track

Depth (In)	Wet Density (lbs/ft^3)	Dry Density (lbs/ft^3)	Moisture (%)	Moisture (lbs/ft^3)
0	109.7	110.5	8.3	8.1
2	111.9	114.6	8.3	8.5
4	112.8	120.5	7.7	8.1
6	115.4	118.9	7.4	8.0
8	119.5	119.9	7.8	8.6

SITE 5 Undisturbed pavement

Depth (In)	Wet Density (lbs/ft^3)	Dry Density (lbs/ft^3)	Moisture (%)	Moisture (lbs/ft^3)
0	105.0	99.9	5.8	5.7
2	108.3	103.2	5.7	5.8
4	110.0	106.5	5.4	5.6
6	111.6	108.5	5.2	5.5
8	116.6	111.9	5.2	5.7

SITE 6 In Track

Depth (In)	Wet Density (lbs/ft^3)	Dry Density (lbs/ft^3)	Moisture (%)	Moisture (lbs/ft^3)
0	122.4	115.5	6.1	7.0
2	124.1	117.2	5.9	6.9
4	125.0	117.9	6.1	7.2
6	127.1	120.1	5.8	7.0
8	126.2	119.1	6.0	7.2

SITE 6 Undisturbed Pavement

Depth (In)	Wet Density (lbs/ft^3)	Dry Density (lbs/ft^3)	Moisture (%)	Moisture (lbs/ft^3)
0	106.7	100.5	6.2	6.3
2	110.3	104.4	5.7	5.9
4	109.1	102.4	6.6	6.7
6	113.5	107.5	5.6	6.0
8	118.7	112.4	5.7	6.4

SITE 7 In Track

Depth (In)	Wet Density (lbs/ft^3)	Dry Density (lbs/ft^3)	Moisture (%)	Moisture (lbs/ft^3)
0	117.8	109.8	7.4	8.1
2	119.7	113.3	5.7	6.4
4	120.7	114.1	5.7	6.5
6	119.6	112.5	6.4	7.2
8	116.8	109.5	6.6	7.3

SITE 7 Undisturbed Pavement

Depth (In)	Wet Density (lbs/ft^3)	Dry Density (lbs/ft^3)	Moisture (%)	Moisture (lbs/ft^3)
0	107.3	102.2	5.0	5.1
2	109.0	103.4	5.4	5.5
4	110.3	105.3	4.7	5.0
6	113.8	107.2	6.1	6.5
8	119.9	114.9	4.3	5.0

SITE 8 In Track

Depth (In)	Wet Density (lbs/ft^3)	Dry Density (lbs/ft^3)	Moisture (%)	Moisture (lbs/ft^3)
0	119.9	113.2	5.9	6.7
2	122.2	114.9	6.3	7.3
4	122.8	116.2	5.7	6.6
6	121.8	114.5	6.3	7.3
8	122.7	116.0	5.8	6.7

Site 8 Undisturbed Pavement

Depth (In)	Wet Density (lbs/ft^3)	Dry Density (lbs/ft^3)	Moisture (%)	Moisture (lbs/ft^3)
0	111.8	106.5	4.9	5.3
2	112.7	106.6	5.7	6.1
4	114.0	107.3	6.2	6.6
6	117.2	111.2	5.4	6.0
8	120.5	114.4	5.3	6.1

SITE 9 In track

Depth (In)	Wet Density (lbs/ft^3)	Dry Density (lbs/ft^3)	Moisture (%)	Moisture (lbs/ft^3)
0	111.9	113.0	6.2	7.0
2	122.4	115.8	5.7	6.6
4	125.7	118.5	6.0	7.2
6	128.1	120.7	6.1	7.4
8	130.2	123.1	5.8	7.2

SITE 9 Undisturbed

Depth (In)	Wet Density (lbs/ft^3)	Dry Density (lbs/ft^3)	Moisture (%)	Moisture (lbs/ft^3)
0	106.6	98.5	7.6	7.4
2	108.9	102.2	6.6	6.7
4	108.2	100.4	7.8	7.8
6	112.3	105.0	6.9	7.3
8	117.5	109.6	7.2	7.9

SITE 10 In Track

Depth (In)	Wet Density (lbs/ft^3)	Dry Density (lbs/ft^3)	Moisture (%)	Moisture (lbs/ft^3)
0	112.5	104.4	7.7	8.1
2	116.4	108.8	7.0	7.6
4	119.8	111.2	7.7	8.5
6	122.4	114.2	7.2	8.3
8	124.3	115.9	7.2	8.4

SITE 10 Undisturbed Pavement

Depth (In)	Wet Density (lbs/ft^3)	Dry Density (lbs/ft^3)	Moisture (%)	Moisture (lbs/ft^3)
0	108.1	101.7	6.3	6.4
2	112.0	104.2	7.5	7.8
4	116.1	109.9	5.7	6.3
6	115.5	109.0	5.9	6.4
8	122.2	114.7	6.5	7.4

SITE 11 In track

Depth (In)	Wet Density (lbs/ft^3)	Dry Density (lbs/ft^3)	Moisture (%)	Moisture (lbs/ft^3)
0	119.0	111.9	6.3	7.1
2	119.3	111.8	6.7	7.5
4	121.2	113.2	7.1	8.0
6	123.5	116.0	6.5	7.5
8	126.7	119.2	6.3	7.5

SITE 11 Undisturbed

Depth (In)	Wet Density (lbs/ft^3)	Dry Density (lbs/ft^3)	Moisture (%)	Moisture (lbs/ft^3)
0	110.6	104.1	6.3	6.5
2	110.4	104.1	6.1	6.4
4	118.9	112.5	5.6	6.4
6	119.8	112.9	6.9	6.1
8	119.2	112.5	6.0	6.9

SITE 12 In track

Depth (In)	Wet Density (lbs/ft^3)	Dry Density (lbs/ft^3)	Moisture (%)	Moisture (lbs/ft^3)
0	110.9	102.8	7.9	8.2
2	112.3	104.6	7.4	7.7
4	111.6	103.2	8.1	8.4
6	112.8	105.1	7.3	7.6
8	113.0	105.6	7.1	7.4

SITE 12 Undisturbed Pavement

Depth (In)	Wet Density (lbs/ft^3)	Dry Density (lbs/ft^3)	Moisture (%)	Moisture (lbs/ft^3)
0	105.4	99.2	6.3	6.3
2	104.8	98.0	6.9	6.8
4	101.6	95.1	6.9	6.5
6	101.7	95.0	7.1	6.7
8	103.4	97.0	6.6	6.4

SITE 13 In track

Depth (In)	Wet Density (lbs/ft^3)	Dry Density (lbs/ft^3)	Moisture (%)	Moisture (lbs/ft^3)
0	111.2	104.5	6.3	6.6
2	112.8	106.5	6.0	6.4
4	112.4	104.7	7.4	7.7
6	113.5	106.8	6.2	6.6
8	113.8	107.3	6.0	6.4

SITE 13 Undisturbed Pavement

Depth (In)	Wet Density (lbs/ft^3)	Dry Density (lbs/ft^3)	Moisture (%)	Moisture (lbs/ft^3)
0	108.5	103.3	5.0	5.2
2	108.2	102.2	5.9	6.0
4	106.1	100.3	5.8	5.8
6	107.5	101.0	6.4	6.4
8	109.9	104.7	4.9	5.2

SITE 14 In Track

Depth (In)	Wet Density (lbs/ft^3)	Dry Density (lbs/ft^3)	Moisture (%)	Moisture (lbs/ft^3)
0	118.5	110.7	7.0	7.8
2	122.6	115.3	6.3	7.3
4	122.1	114.2	6.9	7.8
6	124.5	116.7	6.7	7.8
8	127.9	119.4	7.1	8.5

Site 14 Undisturbed Pavement

Depth (In)	Wet Density (lbs/ft^3)	Dry Density (lbs/ft^3)	Moisture (%)	Moisture (lbs/ft^3)
0	112.9	106.4	6.1	6.4
2	115.5	109.6	5.4	5.9
4	122.1	116.2	5.1	5.9
6	122.3	116.6	4.9	5.7
8	123.9	117.8	5.2	6.1

SITE 15 In Track

Depth (In)	Wet Density (lbs/ft^3)	Dry Density (lbs/ft^3)	Moisture (%)	Moisture (lbs/ft^3)
0	113.6	105.5	7.7	8.1
2	117.2	108.9	7.6	8.3
4	118.7	110.4	7.5	8.3
6	119.3	110.1	8.4	9.3
8	122.2	113.8	7.3	8.4

SITE 15 Undisturbed Pavement

Depth (In)	Wet Density (lbs/ft^3)	Dry Density (lbs/ft^3)	Moisture (%)	Moisture (lbs/ft^3)
0	108.6	102.2	6.3	6.4
2	109.0	103.2	5.5	5.7
4	111.8	105.0	6.5	6.8
6	111.8	106.1	5.4	5.7
8	116.4	110.6	5.3	5.8

APPENDIX G

TRACK SCAR MEASUREMENTS

Table G-1. Track Base and Width Measurements in cm. B indicates a base measurement from the outside of one track scar to the outside of the other track scar of the pair. W indicates a measurement of the width of a single track scar.

1455B cm	1400B cm	1154B cm	01B cm	1015B cm	1042B cm	3JULB cm	1455W cm	1400W cm	1154W cm	01W cm	1015W cm	1042W cm	3JULW cm
251	244	257	267	259	264	240	38	30	43	46	48	48	30
259	246	259	262	257	262	240	38	25	48	46	48	43	40
254	241	262	251	262	264	238	38	25	53	51	53	46	32
254	241	267	257	262	267	238	41	27	61	51	56	51	40
262	244	262	254	259	262	240	41	29	43	58	5	51	31
257	241	269	259	262	264	242	38	30	41	58	56	53	35
257	244	264	262	257	257	241	46	33	38	51	51	51	28
251	241	259	274	257	254	243	46	34	46	48	51	51	30
251	239	262		257	257	240	41	33	41	48	48	58	28
249	249	262		254	251	241	41	30	43	64	41	53	25
251	246	259		254	251	238	41	33	41	48	36	53	30
251	241	262		254	249	240	41	38	36	51	38	51	23
254	239	257		254	249	247	43	36	36	53	41	48	29
246		259		257	254	234	41	36	33	64	43	46	26
244		257		257	254	244	41	38	33		38	43	28
241		257		254	251	241	41	41	30		43	46	25
244		259		257	251	245	38	38	56		43	51	26
251		259		254		244	41	43	51		56	48	25
254		262		254		240	43	41	46		48	51	26
257		264		262		251	38	38	46		41	51	25
262		254		262		250	46	36	43		48	46	26
254		254		254		250	43	38	43		41	51	30
257				251		250	43	38	41		51	53	26
				251		240	41	30	46		58	48	31
				254		243	41	28	41		58	48	32
				259		244	38	30	38		51	41	33
				267		245	38	36	41		48	43	19
				269		244	38	30	41		53	46	34
				274		244	41	30	38		51	46	31
						247	41	30	41		53	48	31
						244	46		38		53		29
						241	41		41				25
						245	46		41				27
						244			41				35
						240			43				27
						251			46				29
						250			46				26
						250							30
						250							33
						240							36

Table G-1 (continued)

1455B cm	1400B cm	1154B cm	01B cm	1015B cm	1042B cm	3JULB cm	1455W cm	1400W cm	1154W cm	01W cm	1015W cm	1042W cm	3JULW cm
						243							24
						244							38
						245							28
						244							33
						244							40
						247							34
													30
													30
													31
													27
													31
													30
													35
													31
													33
													28
													29
													28
													35
													29

Table G-2. One-Sample Statistics for track widths.

Track scar	N	Mean	Std. Deviation	Std. Error Mean
1455WCM	33	41.02	2.55	.44
1400WCM	30	33.57	4.70	.86
1154WCM	37	42.42	6.10	1.00
01WCM	14	52.61	6.01	1.61
1015WCM	31	46.79	9.98	1.79
1042WCM	30	48.77	3.85	.70
3JULWCM	60	29.9333	4.2501	.5487

Table G-3. One-Sample Test for M3A1 Stuart Light Tank Track Width - Test Value = 29.5

Track scar	t	df	Sig. (2-tailed)	Mean Difference	95% Confidence Interval of the Difference Lower	Upper
1455WCM	25.967	32	.000	11.52	10.62	12.43
1400WCM	4.742	29	.000	4.07	2.31	5.83
1154WCM	12.885	36	.000	12.92	10.89	14.96
01WCM	14.383	13	.000	23.11	19.64	26.59
1015WCM	9.639	30	.000	17.29	13.62	20.95
1042WCM	27.376	29	.000	19.27	17.83	20.71
3JULWCM	.790	59	.433	.4333	-.6646	1.5312

Table G-4. One-Sample Test for M3A5 Grant Medium Tank Track Width* - Test Value = 40.6

Track scar	t	df	Sig. (2-tailed)	Mean Difference	95% Confidence Interval of the Difference Lower	Upper
1455WCM	.957	32	.346	.42	-.48	1.33
1400WCM	-8.190	29	.000	-7.03	-8.79	-5.27
1154WCM	1.819	36	.077	1.82	-.21	3.86
01WCM	7.476	13	.000	12.01	8.54	15.49
1015WCM	3.449	30	.002	6.19	2.52	9.85
1042WCM	11.605	29	.000	8.17	6.73	9.61
3JULWCM	-19.440	59	.000	-10.6667	-11.7646	-9.5688

*NOTE: Track widths for the M3A5 can be 40.6 or 42.1 cm depending on the track type installed on the tank.

Table G-5. One-Sample Test for M3A5 Grant Medium Tank* & M4 Sherman Medium Tank Track widths - Test Value = 42.1

Track scar	t	df	Sig. (2-tailed)	Mean Difference	95% Confidence Interval of the Difference Lower	Upper
1455WCM	-2.422	32	.021	-1.08	-1.98	-.17
1400WCM	-9.938	29	.000	-8.53	-10.29	-6.77
1154WCM	.324	36	.748	.32	-1.71	2.36
01WCM	6.543	13	.000	10.51	7.04	13.99
1015WCM	2.613	30	.014	4.69	1.02	8.35
1042WCM	9.474	29	.000	6.67	5.23	8.11
3JULWCM	-22.174	59	.000	-12.1667	-13.2646	-11.0688

*NOTE: Track widths for the M3A5 can be 40.6 or 42.1 cm depending on the track type installed on the tank.

Table G-6. One-Sample Test for M60A3 MBT track width - Test Value = 71.12

Track scar	t	df	Sig. (2-tailed)	Mean Difference	95% Confidence Interval of the Difference Lower	Upper
1455WCM	-67.808	32	.000	-30.10	-31.00	-29.19
1400WCM	-43.749	29	.000	-37.55	-39.31	-35.79
1154WCM	-28.607	36	.000	-28.70	-30.73	-26.66
01WCM	-11.515	13	.000	-18.51	-21.98	-15.03
1015WCM	-13.570	30	.000	-24.33	-28.00	-20.67
1042WCM	-31.758	29	.000	-22.35	-23.79	-20.91
3JULWCM	-75.064	59	.000	-41.1867	-42.2846	-40.0888

Table G-7. One-Sample Test for a Civilian Dodge Dakota 4x4 wheel width (for comparison) - Test Value = 22.86

Track scar	t	df	Sig. (2-tailed)	Mean Difference	95% Confidence Interval of the Difference	
					Lower	Upper
1455WCM	40.928	32	.000	18.16	17.26	19.07
1400WCM	12.479	29	.000	10.71	8.95	12.47
1154WCM	19.505	36	.000	19.56	17.53	21.60
01WCM	18.515	13	.000	29.75	26.28	33.23
1015WCM	13.342	30	.000	23.93	20.26	27.59
1042WCM	36.810	29	.000	25.91	24.47	27.35
3JULWCM	12.891	59	.000	7.0733	5.9754	8.1712

Table G-8. One-Sample Statistics Track Base Measurements

	N	Mean	Std. Deviation	Std. Error Mean
1455BCM	23	252.67	5.30	1.10
1400BCM	13	242.86	3.03	.84
1154BCM	22	260.12	3.81	.81
01BCM	8	260.67	7.30	2.58
1015BCM	29	257.94	5.28	.98
1042BCM	17	256.54	5.96	1.44
3JULBCM	46	243.6087	4.0358	.5951

Table G-9. One-Sample Test for M3A1 Stuart Light Tank track base - Test Value = 224

Track scar	t	df	Sig. (2-tailed)	Mean Difference	95% Confidence Interval of the Difference Lower	Upper
1455BCM	25.954	22	.000	28.67	26.38	30.97
1400BCM	22.446	12	.000	18.86	17.03	20.69
1154BCM	44.433	21	.000	36.12	34.43	37.81
01BCM	14.200	7	.000	36.67	30.56	42.77
1015BCM	34.592	28	.000	33.94	31.93	35.95
1042BCM	22.523	16	.000	32.54	29.48	35.60
3JULBCM	32.953	45	.000	19.6087	18.4102	20.8072

Table G-10. One-Sample Test for M3A51 Grant Medium Tank track base – 272

Track scar	t	df	Sig. (2-tailed)	Mean Difference	95% Confidence Interval of the Difference Lower	Upper
1455BCM	-17.491	22	.000	-19.33	-21.62	-17.03
1400BCM	-34.671	12	.000	-29.14	-30.97	-27.31
1154BCM	-14.616	21	.000	-11.88	-13.57	-10.19
01BCM	-4.389	7	.003	-11.33	-17.44	-5.23
1015BCM	-14.328	28	.000	-14.06	-16.07	-12.05
1042BCM	-10.701	16	.000	-15.46	-18.52	-12.40
3JULBCM	-47.712	45	.000	-28.3913	-29.5898	-27.1928

Table G-11. One-Sample Test for M4 Sherman Medium Tank track base - Test Value = 262

Track scar	t	df	Sig. (2-tailed)	Mean Difference	95% Confidence Interval of the Difference Lower	Upper
1455BCM	-8.440	22	.000	-9.33	-11.62	-7.03
1400BCM	-22.772	12	.000	-19.14	-20.97	-17.31
1154BCM	-2.314	21	.031	-1.88	-3.57	-.19
01BCM	-.516	7	.622	-1.33	-7.44	4.77
1015BCM	-4.136	28	.000	-4.06	-6.07	-2.05
1042BCM	-3.779	16	.002	-5.46	-8.52	-2.40
3JULBCM	-30.907	45	.000	-18.3913	-19.5898	-17.1928

Table G-12. One-Sample Test for M60A3 MBT track base - Test Value = 3.63

Track scar	t	df	Sig. (2-tailed)	Mean Difference	95% Confidence Interval of the Difference Lower	Upper
1455BCM	225.411	22	.000	249.04	246.75	251.34
1400BCM	284.672	12	.000	239.23	237.40	241.06
1154BCM	315.531	21	.000	256.49	254.80	258.18
01BCM	99.543	7	.000	257.04	250.93	263.14
1015BCM	259.184	28	.000	254.31	252.30	256.32
1042BCM	175.055	16	.000	252.91	249.85	255.97
3JULBCM	403.291	45	.000	239.9787	238.7802	241.1772

Table G-13. One-Sample Test for Civilian Dodge Dakota 4x4 wheel base (for comparison) - Test Value = 1.78

Track scar	t	df	Sig. (2-tailed)	Mean Difference	95% Confidence Interval of the Difference Lower	Upper
1455BCM	227.085	22	.000	250.89	248.60	253.19
1400BCM	286.874	12	.000	241.08	239.25	242.91
1154BCM	317.807	21	.000	258.34	256.65	260.03
01BCM	100.260	7	.000	258.89	252.78	264.99
1015BCM	261.069	28	.000	256.16	254.15	258.17
1042BCM	176.336	16	.000	254.76	251.70	257.82
3JULBCM	406.400	45	.000	241.8287	240.6302	243.0272

APPENDIX H

SURFACE PARTICLE SIZE

Table H-1. Pebble surface area

Image	In	Out	Total Pixels in image	Total Pixels without Calibration Cards	# of Pebbles Present	Average Pebble Area in mm^2
P1010003_OUT_Crop_Level		X	68392	53457	48	42.99
P1010004_IN_Crop_Level	X		64152	50787	67	30.32
P1010005_OUT_Crop_Level		X	66761	51058	26	75.80
P1010006_IN_Crop_Level	X		65600	50149	90	21.68
P1010007_OUT_Crop_Level		X	67973	51507	15	126.99
P1010008_IN_Crop_Level	X		62818	48576	80	24.39
P1010009_OUT_Crop_Level		X	67218	51876	38	53.32
P1010010_IN_Crop_Level	X		62880	52038	26	79.74
P1010011_OUT_Crop_Level		X	65800	50764	15	133.76
P1010012_IN_Crop_Level	X		67671	52736	80	26.26
P1010013_OUT_Crop_Level		X	69056	52621	38	54.51
P1010014_IN_Crop_Level	X		65800	50764	64	31.23
P1010015_OUT_Crop_Level		X	66400	52300	21	96.89
P1010016_IN_Crop_Level	X		68804	52520	46	44.42
P1010017_OUT_Crop_Level		X	67014	52938	22	94.35
P1010018_IN_Crop_Level	X		65538	51777	73	27.59
P1010019_OUT_Crop_Level		X	66033	51777	25	79.94
P1010020_IN_Crop_Level	X		66559	50985	45	43.90
P1010021_OUT_Crop_Level		X	66963	52520	21	97.29
P1010022_IN_Crop_Level	X		64680	50440	70	28.14
P1010023_OUT_Crop_Level		X	63535	49020	19	100.77
P1010024_IN_Crop_Level	X		68175	53227	59	34.96
P1010025_OUT_Crop_Level		X	66963	52520	20	101.36
P1010026_IN_Crop_Level	X		66458	51084	110	18.21
P1010027_OUT_Crop_Level		X	67367	52100	27	74.77
P1010028_IN_Crop_Level	X		63840	49210	85	22.43
P1010029_OUT_Crop_Level		X	64582	50496	20	97.84
P1010030_IN_Crop_Level	X		64092	49632	59	33.12
P1010031_OUT_Crop_Level		X	68907	52700	29	70.14
P1010032_IN_Crop_Level	X		66033	50764	51	38.42
P1010033_OUT_Crop_Level		X	70140	55125	32	65.71
P1010034_IN_Crop_Level	X		64778	49920	56	34.95
P1010035_OUT_Crop_Level		X	64311	50304	18	107.45
P1010036_IN_Crop_Level	X		67728	52200	31	64.74
P1010037_OUT_Crop_Level		X	65340	49920	18	107.47
P1010038_IN_Crop_Level	X		67367	52600	134	15.15
P1010039_OUT_Crop_Level		X	69360	53530	50	41.00
P1010040_IN_Crop_Level	X		66400	51156	87	22.61
P1010041_OUT_Crop_Level		X	65900	51500	35	57.70
P1010042_IN_Crop_Level	X		70035	53972	115	17.97
P1010043_OUT_Crop_Level		X	64582	50149	27	72.26

Table H-1 (continued)

Image	In	Out	Total Pixels in image	Total Pixels without Calibration Cards	# of Pebbles Present	Average Pebble Area in mm^2
P1010044_IN_Crop_Level	X		66231	51216	113	17.43
P1010045_OUT_Crop_Level		X	64152	49686	29	70.49
P1010046_IN_Crop_Level	X		67670	52400	110	18.31
P1010047_OUT_Crop_Level		X	64408	50304	49	39.47
P1010048_IN_Crop_Level	X		68175	52900	136	14.67
P1010049_OUT_Crop_Level		X	66000	52100	46	44.77
P1010050_IN_Crop_Level	X		66900	52173	133	14.68
P1010051_OUT_Crop_Level		X	62759	49664	40	49.66
P1010052_IN_Crop_Level	X		65464	51646	81	24.32
P1010053_OUT_Crop_Level		X	64647	49858	57	35.27
P1010054_IN_Crop_Level	X		62985	49068	102	18.64
P1010055_OUT_Crop_Level		X	70304	53754	49	41.52
P1010056_IN_Crop_Level	X		66300	51900	160	12.57
P1010057_OUT_Crop_Level		X	65934	51352	85	23.23
P1010058_IN_Crop_Level	X		66800	52500	104	19.41
P1010059_OUT_Crop_Level		X	68850	53429	32	63.20
P1010060_IN_Crop_Level	X		65268	51156	112	17.42
P1010061_OUT_Crop_Level		X	66054	52520	36	56.53
P1010062_IN_Crop_Level	X		68744	52836	84	24.37
P1010063_OUT_Crop_Level		X	63168	49920	34	57.12
P1010064_IN_Crop_Level	X		65835	51058	121	16.42
P1010065_OUT_Crop_Level		X	66559	52621	36	56.64
P1010066_IN_Crop_Level	X		66458	52217	107	18.91
P1010067_OUT_Crop_Level		X	68701	53227	28	72.80
P1010068_IN_Crop_Level	X		65142	50862	98	19.95

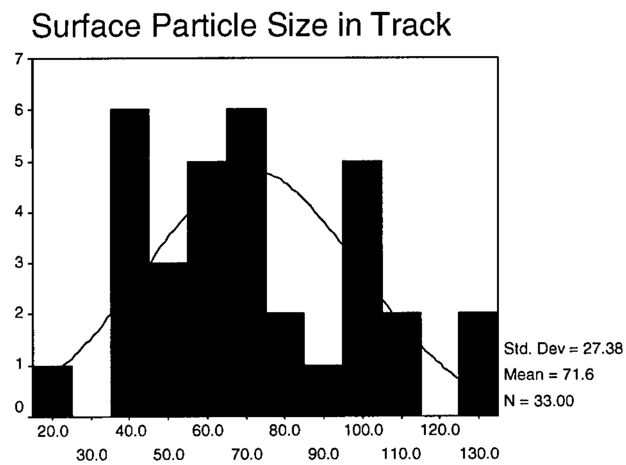


Figure H-1. Histogram of surface particle size from the surface of track scars.

Table H-1. Descriptive statistics for particle size on the surface of track scarred pavement.

	N Statistic	Minimum Statistic	Maximum Statistic	Mean Statistic	Std. Deviation statistic	Skewness Statistic	Std. Error	Kurtosis Statistic	Std. Error
SIZEIN	33	12.57	79.74	27.1918	14.3976	2.161	.409	5.461	.798
Valid N (listwise)	33								

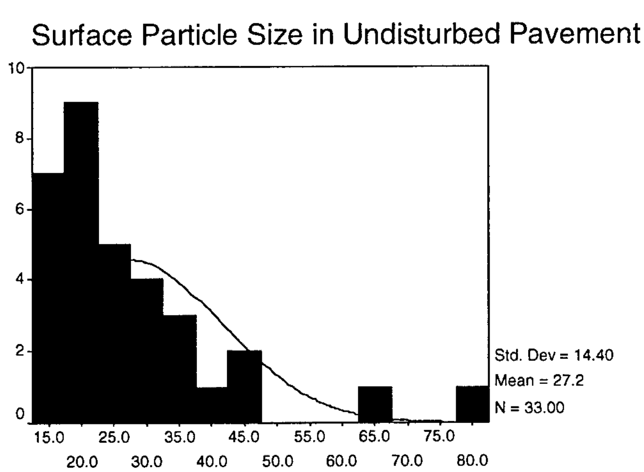


Figure H-2. Histogram of surface particle sizes from the surface of undisturbed pavement.

Table H-1. Descriptive statistics for particle size on the surface of undisturbed pavement.

	N Statistic	Minimum Statistic	Maximum Statistic	Mean Statistic	Std. Deviation Statistic	Skewness Statistic	Std. Error	Kurtosis Statistic	Std. Error
SIZEOUT	33	23.23	133.76	71.6064	27.3784	.468	.409	-.450	.798
Valid N (listwise)	33								

Table H-3. One-Sample Kolmogorov-Smirnov Test for particle sizes on the surface of track scarred pavement.

N		SIZE IN 33
Normal Parameters	Mean	27.1918
	Std. Deviation	14.3976
Most Extreme Differences	Absolute	.183
	Positive	.183
	Negative	-.162
Kolmogorov-Smirnov Z		1.052
Asymp. Sig. (2-tailed)		.218

a Test distribution is Normal.
b Calculated from data.

Table H-4. One-Sample Kolmogorov-Smirnov Test for particle sizes on the surface of undisturbed pavement.

N		SIZE OUT 33
Normal Parameters	Mean	71.6064
	Std. Deviation	27.3784
Most Extreme Differences	Absolute	.118
	Positive	.118
	Negative	-.100
Kolmogorov-Smirnov Z		.681
Asymp. Sig. (2-tailed)		.743

a Test distribution is Normal.
b Calculated from data.

Table H-5. Paired Samples Statistics for both track scarred and undisturbed pavement surface particle sizes.

		Mean	N	Std. Deviation	Std. Error Mean
Pair 1	SIZEIN	27.1918	33	14.3976	2.5063
	SIZEOUT	71.6064	33	27.3784	4.7660

Table H-6. Paired Samples Correlations for both track scarred and undisturbed pavement surface particle sizes.

		N	Correlation	Sig.
Pair 1	SIZEIN & SIZEOUT33		.222	.214

Table H-7. Paired Samples Test for both track scarred and undisturbed pavement surface particle sizes.

	Paired Differences	Mean	Std. Deviation	Std. Error Mean	95% Confidence Interval of the Difference Lower	Upper	t	df	Sig. (2-tailed)
Pair 1	IN - OUT	-44.4145	27.9614	4.8675	-54.3292	-34.4999	-9.125	32	.000

APPENDIX I

SURFACE PARTICLE SPHERICITY

Table I-1. Sphericity measurements of clasts from the surface of track scars.

Long	Intermediate	Short	Sphericity	Long	Intermediate	Short	Sphericity
2	1.2	0.7	0.59	1.1	0.8	0.3	0.47
1.6	1.3	0.3	0.35	1.1	0.5	0.4	0.67
1	0.6	0.4	0.65	1	0.5	0.25	0.50
1	0.7	0.5	0.71	0.75	0.75	0.3	0.55
0.9	0.9	0.4	0.59	0.85	0.5	0.25	0.53
1.2	0.6	0.5	0.71	1.1	0.6	0.35	0.57
0.9	0.7	0.2	0.40	1	0.5	0.2	0.43
1	0.5	0.3	0.57	0.65	0.4	0.25	0.62
0.7	0.6	0.3	0.60	0.9	0.4	0.25	0.56
1.2	0.7	0.3	0.48	0.5	0.4	0.3	0.77
1.1	0.7	0.4	0.60	0.6	0.4	0.1	0.35
0.9	0.7	0.3	0.53	0.4	0.25	0.1	0.47
0.7	0.6	0.4	0.73	0.3	0.1	0.05	0.44
0.6	0.6	0.4	0.77	0.1	0.1	0.05	0.63
0.9	0.4	0.2	0.48	0.05	0.05	0.05	1.00
0.9	0.5	0.2	0.45	0.1	0.05	0.05	0.80
0.5	0.4	0.3	0.77	3.2	1.4	0.7	0.48
0.6	0.4	0.2	0.55	2.1	1.2	0.6	0.53
0.7	0.4	0.2	0.53	1.6	0.9	0.75	0.73
0.7	0.5	0.2	0.49	1.3	1	0.3	0.41
0.5	0.4	0.2	0.59	1.5	1.1	0.3	0.38
0.5	0.3	0.2	0.65	1.1	0.7	0.6	0.78
0.5	0.4	0.1	0.37	1.2	1	0.5	0.60
0.6	0.3	0.1	0.39	1.1	0.8	0.4	0.57
0.3	0.3	0.3	1.00	1.2	0.7	0.3	0.48
0.4	0.3	0.2	0.70	0.8	0.8	0.25	0.46
0.4	0.3	0.2	0.70	1	0.8	0.3	0.49
0.2	0.1	0.1	0.80	1.2	0.8	0.4	0.55
1.9	1.25	0.8	0.65	0.9	0.6	0.4	0.67
1.55	1.4	0.6	0.55	1.1	0.7	0.5	0.69
1.4	1	0.35	0.45	0.8	0.4	0.3	0.66
1.7	0.7	0.55	0.64	1.1	0.5	0.35	0.61
1.45	0.95	0.4	0.49	0.6	0.5	0.25	0.60
1	0.9	0.55	0.70	0.9	0.45	0.4	0.74
1.2	1.1	1	0.91	0.7	0.6	0.5	0.84
1.05	0.6	0.4	0.64	0.8	0.4	0.25	0.58
1.1	0.85	0.4	0.56	0.9	0.6	0.25	0.49
1.3	1	0.3	0.41	0.75	0.55	0.3	0.61
0.9	0.7	0.6	0.83	0.75	0.55	0.4	0.73
1.2	1	0.6	0.67	0.9	0.7	0.3	0.53
1.3	0.7	0.4	0.56	0.8	0.6	0.35	0.64
1.1	0.7	0.4	0.60	0.8	0.5	0.2	0.47

Table I-1 (continued)

Long	Intermediate	Short	Sphericity
0.8	0.45	0.2	0.48
0.7	0.55	0.35	0.69
0.7	0.6	0.4	0.73
0.6	0.4	0.2	0.55
0.75	0.25	0.25	0.70
0.7	0.3	0.15	0.48
0.6	0.3	0.25	0.71
0.65	0.2	0.2	0.68

Table I-2. Sphericity measurements of clasts from the surface of undisturbed pavement.

Long	Intermediate	Short	Sphericity
4.3	2.5	1.9	0.70
4.1	2.9	1.7	0.63
2.2	1.4	0.7	0.55
2.7	1.6	0.7	0.49
1.9	1.6	0.5	0.44
1.6	1.3	1.2	0.89
1.7	1.2	1.2	0.89
1.9	1.2	0.7	0.60
2	1.1	0.4	0.42
0.9	0.8	0.7	0.88
1.5	1.2	0.7	0.65
0.8	0.8	0.6	0.83
1.4	1.2	0.4	0.46
2	1.1	0.7	0.61
1.4	1.2	0.4	0.46
0.9	1	0.5	0.66
0.9	0.9	0.6	0.77
1.4	0.8	0.5	0.61
1.4	1.2	0.5	0.53
1	0.9	0.4	0.57
1	0.7	0.5	0.71
0.8	0.5	0.3	0.61
0.7	0.5	0.3	0.64
0.8	0.4	0.2	0.50
0.6	0.4	0.2	0.55
0.5	0.4	0.2	0.59
0.3	0.3	0.1	0.48
0.2	0.1	0.1	0.80

Long	Intermediate	Short	Sphericity
6.1	4.6	1.3	0.40
7.8	5.15	1.5	0.39
4.85	3.5	0.6	0.28
4.35	2.8	1.9	0.67
4.2	2.9	1.3	0.52
3.6	2.5	1.2	0.55
3.4	1.65	1.1	0.60
4.2	1	0.75	0.52
3.25	2.2	0.85	0.47
3.4	2.15	0.4	0.28
2.75	2.3	1.2	0.61
2.9	1.55	1.05	0.63
3.7	1.25	0.8	0.52
2.2	1.05	0.65	0.57
2.1	0.7	0.6	0.63
1.8	1.2	0.75	0.64
1.6	0.9	0.6	0.63
1.6	0.8	0.5	0.58
1.5	0.9	0.65	0.68
1.2	0.7	0.5	0.67
1.1	0.95	0.5	0.62
1.1	0.5	0.45	0.72
0.5	0.4	0.15	0.49
0.3	0.2	0.05	0.35
0.3	0.2	0.1	0.55
0.2	0.1	0.05	0.50
3.2	1.8	1.15	0.62
3.3	2.2	1.7	0.74
2.9	1.6	1.15	0.66
4	2.95	1.65	0.62
6.7	5.7	2.35	0.53
3.7	3.4	1.91	0.66
5.83	2.8	2.2	0.67
3.11	2.3	1.4	0.65
2.6	1.81	0.7	0.47
1.3	1.3	1.1	0.90
3.1	1.5	1.3	0.72
2.8	1.8	1.4	0.73
2	1.1	0.83	0.68
2.5	1.5	0.6	0.46
1.9	1.2	1	0.76
3.83	2.3	1.5	0.64
2	1.4	0.5	0.45

Table I-2 (continued)

Long	Intermediate	Short	Sphericity
5.1	2.1	1.5	0.60
2.8	1.5	1.1	0.66
1.6	0.9	0.8	0.77
2.2	1.7	0.6	0.46
2.2	0.9	0.8	0.69
1.8	1.5	0.5	0.46
2.3	1	0.9	0.71
1.8	1.7	0.5	0.44
1.5	1.3	0.8	0.69
1.7	1.1	0.6	0.58

Long	Intermediate	Short	Sphericity
1.9	1.2	0.4	0.42
2	1.2	0.6	0.53
1.1	0.8	0.6	0.74
0.9	0.8	0.6	0.80
0.4	0.3	0.25	0.81
1.4	0.7	0.4	0.55
0.5	0.4	0.1	0.37
0.4	0.3	0.1	0.44
0.3	0.3	0.15	0.63
0.1	0.1	0.1	1.00
0.1	0.1	0.1	1.00

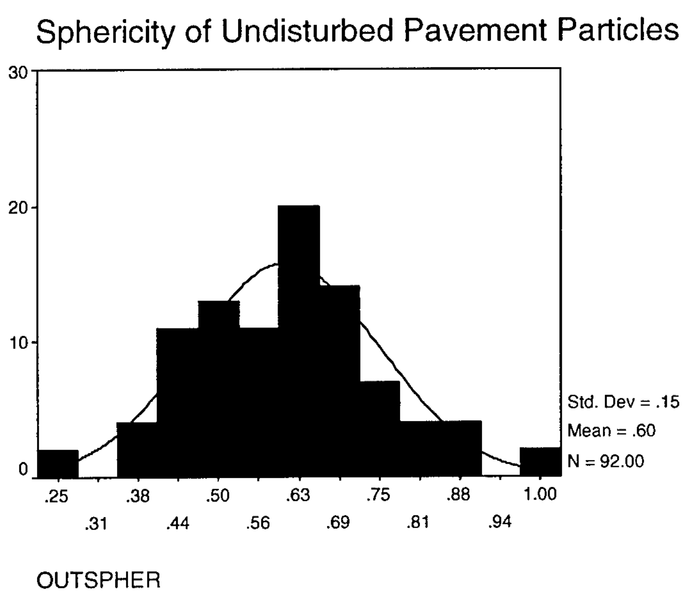


Figure I-1. Histogram of sphericity results of surface particles from track scarred pavement.

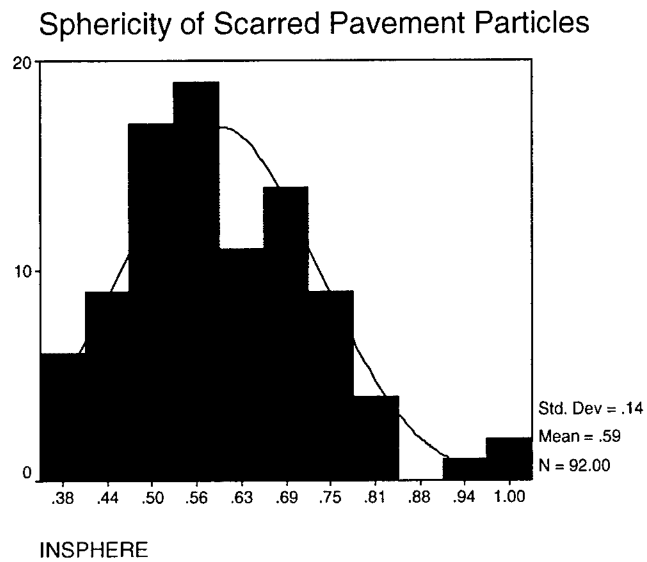


Figure I-2. Histogram of sphericity results of surface particles from undisturbed pavement.

Table I-3. Descriptive Statistics comparing sphericity of particles on the surface of track scars and undisturbed pavement.

	N Statistic	Minimum Statistic	Maximum Statistic	Mean Statistic	Std. Deviation Statistic	Skewness Statistic	Std. Error	Kurtosis Statistic	Std. Error
OUT	92	.28	1.00	.6046	.1450	.320	.251	.292	.498
Valid N (listwise)	92								
IN	92	.35	1.00	.5948	.1359	.574	.251	.453	.498
Valid N (listwise)	92								

APPENDIX J

AV HORIZON DEPTH

Table J-1. Depths (in cm) of Av Horizon measured in the field. The average in track depth is 3.6 cm. The average depth in undisturbed pavement is 2.3 cm.

In Track Scars	In Track Scars	In Undisturbed Pavement	In Undisturbed Pavement
4	4.1	2	3
3	5.3	3	2
3.5	3.8	2.8	1.5
4	3.5	2	1
3.3	4	2	2.9
3.5	2.5	2.5	2.6
3.6	3	2.5	2.6
3.5	3.8	3	3
3.8	3.9	2.6	2.4
3.5	3.5	3	2.1
4	3.8	2.2	2.4
3.8	2.6	2.3	3
3.5	3	3.2	3.4
3.9		2.6	3
		2.4	1
		2.5	1.8
		2	3
		2.1	3.5

APPENDIX K

MOISTURE PENETRATION DEPTH

Table K-1. Depths (in cm) of moisture penetration measured in the field. The average in track depth is 5.7 cm. The average depth in undisturbed pavement is 3.4 cm.

In Track Scars	In Track Scars	In Undisturbed Pavement	In Undisturbed Pavement
5	5.5	4.5	3.4
5.5	5	3.8	3.9
5.9	5.4	3	4
5.5	5.7	4.5	3.3
6	6.2	4.5	4.6
5.4	5.9	2.3	3.2
6	6.3	3.8	3.5
5.9	6.5	3.5	3.5
5.4	7	3.5	3
5.3	5.5	4	3.6
4.9	6	3.9	3.5
5	6	3.8	4.8
6		3.9	3.8
		4	4.5
		4.1	2.8
		3.4	3.2
		2.8	